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AUGUST 1952

ICE-DAMMED LAVAS FROM CLINKER MOUNTAIN, SOUTHWESTERN BRITISH COLUMBIA

W. H. MATHEWS

ABSTRACT. Lava flows from Clinker Mountain exhibit normal gradients and surface character wherever they came to rest at altitudes of more than about 4,000 feet, but distinctly anomalous features where they came to rest at appreciably lower levels. These anomalies include (1) precipitous, locally concave, terminal faces up to 1,500 feet high, subject to major landsliding, (2) unusual thickness of lava, as much as 800 feet in a single flow, and (3) accretion of lava as dribbles on at least one precipitous lava front. These anomalies are attributed to ponding of lava against the Cordilleran ice sheet at a time when it still filled valleys up to approximately the 4,000 foot level.

INTRODUCTION

VOLCANIC activity in close proximity to bodies of glacial ice has been demonstrated in Iceland (Nielsen, 1937; Noe-Nygaard, 1940) and in the Aleutian chain on Umnak Island (Byers *et al.*, 1947) and on Great Sitkin Island (Simons and Mathewson, 1947). Activity in glacial environments has also been inferred in Iceland (Peacock, 1926; Nielsen and Noe-Nygaard, 1936; Noe-Nygaard, 1940) and in British Columbia (Mathews, 1947, 1951b, 1952). Evidence suggesting the proximity of ice at the time of extrusion includes (1) the occurrence in the volcanic rocks of striated boulders, such as could have been dropped from the overlying glacier, plus the widespread development of breccia and pillows attributable to rapid quenching in meltwater or in water-soaked pyroclastic rocks under the ice, or (2) abnormal structures indicative of extrusion into standing meltwater or against ice, together with conformable relations with glacial till. The products of the volcanic activity may be described as *subglacial* if laid down entirely beneath the ice, as *intraglacial* if surrounded on all sides but not covered by ice at time of deposition, and as *supraglacial* if deposited partly or entirely

on the surface of the ice. Still a fourth class can be inferred, that in which the volcanic products are deposited against the margin of the ice. An example from the Mount Garibaldi map-area in southwestern British Columbia, the lava of Clinker Mountain, also known as Red Mountain and Mount Price, is believed to fall in the last-mentioned class. Geological investigation of this volcano indicates that the cone itself was built after the last Cordilleran ice sheet had receded from the uplands on which it was founded, for its surface exhibits the common characteristics of lava flows of subaerial origin, but little modified by weathering and erosion. However, where the latest flows from this volcano reached relatively low ground their termini exhibit such unusual thickness, steepness, and structure as to suggest that the lava had been impounded by the wasting ice sheet.

DESCRIPTION

The central mass of Clinker Mountain consists of a steep, truncated cone rising to an altitude of 6,721 feet, almost 2,000 feet above Garibaldi Lake which now laps against its northern flank (fig. 1). Its broad summit is marked by a shallow depression, the former vent. On the east, the lava buries an older glaciated cone or dome of buff-colored dacite. Quartz diorite is exposed at an altitude of 6,100 feet on the ridge southwest of Clinker Mountain and at an altitude of 5,500 feet at the southeast base of the cone. Though Clinker Mountain has been built almost on the crest of an older ridge, the relatively small bulk of the cone is enhanced by its long northern slope which extends not merely to the level of Garibaldi Lake (altitude 4,816 feet) but continues to a depth of about 800 feet below its surface. The form of the main mass of the mountain is complicated by two satellites, one a steep-sided cone on its northern slope, the other a breached ring on its southwestern shoulder.

Two lava flows, less conspicuous than the main cone itself as seen from the ground, but greater in both areal extent and volume, escaped from the southwestern satellite of Clinker Mountain. One of these flows swept down the northwestern slope of the mountain, spread out at its foot, buried the granitic upland and filled the neighboring valley of Rubble Creek to a depth of at least 800 feet, thereby creating the dam

which now ponds the waters of Garibaldi Lake. The other flow swept down the southern slope of the cone into the valley of Culliton Creek and thence westward for 3 miles. The head of each flow lies at a break in the crater wall of the southwestern satellite and though one flow may have breached the ring at a second point long after its counterpart had broken through the opposite wall, it seems more probable that the two flows emerged simultaneously from the common vent.

The southern flow descends from its source 1,500 feet in its first mile, then, sweeping west along the valley of Culliton Creek, it descends 500 feet in the next 1½ miles and 1,500 feet in the last mile of its course. On the slope of the cone the thickness of lava still remaining is small, possibly exceeding

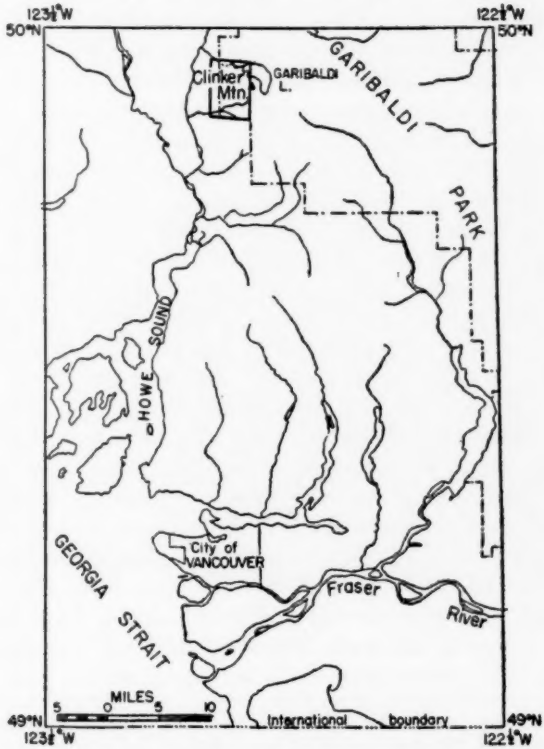

Fig. 1. Index map showing location of Clinker Mountain. Area covered by aerial photographs outlined with solid line.

200 feet only along the levees which here mark the lateral limits of the flow. In the valley itself the lava may locally attain a thickness of 1,000 feet, and it terminates in a scarp, now partly buried by talus, of almost this height. A subsidiary tongue of lava extends southwest from the main flow into the mouth of a large tributary valley. A second and smaller tongue extends for ¼ mile from the northern end of the main flow. The terminal face of the flow is thus distinctly concave. Culliton Creek has now cut through the southern lava tongue in a sheer-walled canyon about 800 feet deep and roughly 550 feet wide at its brim. This creek has sapped part of the lava front (plate 1) but the steep terminal face appears to be essentially an original feature. Relics of the flow are not found along the valley floor or on the lower slopes of the valley walls below the present terminal scarp. Both the shape and the height of the terminal face are distinctly anomalous.

The drainage disturbance brought about by this flow is clearly apparent. Above the point where the flow joins the valley, the valley floor is broad, underlain in part by a flat outwash plain aggraded by the heavily laden stream leaving the north part of Warren Glacier and in part by hummocky moraine burying stagnant ice left by the south half of this same glacier. The recent ravine of Culliton Creek leaving this part of the valley follows the contact of the flow with the south wall of the valley, becoming deeper with distance until the spectacular canyon near the end of the flow is reached. A more recent disturbance of drainage has been caused by the advance of Warren Glacier, probably in the early 1800's (Mathews, 1951a), and the construction of a terminal moraine which has diverted waters from the outwash plain onto the surface of the lava flow. A tortuous course is now followed by this stream over the flow for a distance of almost a mile. Dead and rotting stumps remain standing in its waters. A quarter of a mile west of the moraine a lava wall only 15 feet high separates the newly diverted stream from the much deeper valley to the south. The absence of any significant cutting by this stream after fully a century of occupation pro-

Plate 1. Stereoscopic aerial photos of southern flow from Clinker Mountain. Limits of the flow indicated by a dotted line where they are not obvious from topography.

British Columbia Government air photographs.

BC 866:69
2 MILES, APPROX.
BC 866:68
ASTRONOMIC NORTH
CULLITON CR.
+1000ft

BC 866:66

BC 866:67

ASTRONOMIC NORTH

2 MILES, APPROX.

vides a striking contrast with the deep canyon of Culliton Creek farther west and clearly indicates that the age of this canyon must be measured in thousands of years.

The main part of the flow on the northwest side of Clinker Mountain descends 1,100 feet in the first mile of its course and 1,500 feet in the remaining 2 miles. It ends in a convex rubble face 200 to 300 feet high, much like the flow termini of many of the more acid lavas elsewhere in the world but wholly unlike the terminus of the Culliton Creek flow only 2 miles to the south.

To anyone standing on the central part of the flow, its surface seems to consist of a totally irregular jumble of angular reddened blocks, some many feet in diameter, some teetering and some firmly lodged, some with several smooth faces, others scoriaceous throughout. Between these blocks are numerous cavities extending to unknown depths, some large enough to admit the entrance of a human, but many of a size that only small animals find shelter within them. The apparently complete chaos of this surface is resolved into several distinct patterns if seen from the air (plates 1, 2). The main lava stream, for example, is bounded by two conspicuous levees such as characterize many lava flows throughout the world. Each of the levees of the Clinker Mountain flow has from one to three crests which near its source rise as much as 300 feet above the flat-floored "trough" along the axis of the flow. The depth of this trough or "lava gutter" below the adjoining levees diminishes downstream until about a mile from the terminus the levees lose their identity and the upper surface of the flow extends without sharp break from one lateral margin to the other. The levees of the upper part of the flow, like the lateral walls in the lower part, have clearly been built by accumulation of blocky debris deposited along the flank of the flow and left, like lateral moraines, as the more fluid lava between them drained away. Downstream, where this fluid lava came to rest, the central part of the flow is filled to the level of its walls.

A pattern of low, closely-spaced arcuate wrinkles shows on

Plate 2. Stereoscopic aerial photos of northwest flow from Clinker Mountain. Limits of the flow indicated by a dotted line where they are not obvious from topography.

British Columbia Government air photographs.

the lava surface between the levees, each wrinkle convex downstream. This pattern evidently reflects the more rapid movement of lava in midstream than along the margins of the flow.

A series of lava lobes extends from the margins of the central flow on either side. The surfaces of these lobes are marked by concentric ridges like those within the central trough of the main flow. Several buckles in the otherwise continuous lines of the levees are situated at the foci of concentric ridges of several of these lobes and evidently mark the points where lava escaped from the central flow to form the lobes. With one possible exception, however, the levees are only bent, not breached, at these points and the lava from the central flow must have passed through, not over, its confining walls.

The form of the two main lobes on the south side of the flow was clearly influenced by the pre-existing topography, the lava spreading down valleys and into recesses. The lava did not, however, form a flat plain and though it entered the mouths of recesses it did not completely fill them, leaving, instead, hollows now occupied by small lakes.

Whatever effect the pre-existing topography on the north side of the flow may have had on the form of the lava lobes, the lobes themselves have played an important part in the development of the present topography. The easternmost lobe now appears as a conspicuous if low promontory extending for almost half a mile into Garibaldi Lake, and soundings reveal that the lava extends beneath the surface of the lake for another half mile. The next lobe to the west extends for about half a mile from the central flow and, coming in contact with the older rocks of the north wall of Rubble Creek Valley, it has created the dam which holds back the waters of Garibaldi Lake. Two of the low arcuate ridges on the east side of this lobe are now partly submerged by the water and give rise to a double chain of islets known locally as "The Battleships." A few scattered trees, standing like masts on these islets, accentuate the similarity to a fleet of naval craft. The third lava lobe also extended to the north wall of the valley and, in turn, formed a dam which holds back the waters of Lesser Lake and, by blocking a tributary valley from the north, it created still another and smaller body of water, Barrier Lake. To the west of the outlet of Barrier Lake the face of this lobe and the north wall of the valley diverge and no other body

of water exists, or has existed, along the contact. The fourth and westernmost lobe did not reach the north wall of the valley.

An especially fine vertical cross-section of the third lava lobe is revealed in a spectacular cliff known as "The Barrier," a half mile long and up to 800 feet high. Flow planes in the lava, bowed downward in the middle part of the cliff section and apparently conforming with the base of the flow, consist of alternating layers a few inches to a few feet thick of dark reddish and dark gray dacite. A variety of joint patterns can be recognized. Columnar jointing on a grand scale is developed, for example, near the western end of the cliff; tabular jointing is conspicuous in several other parts. Steep joints predominate in all but the uppermost 200 feet of the lava and are partly responsible for the steepness of the cliff. The uppermost 200 feet of the lava is, however, made up of highly fractured red dacite and dacite rubble like that seen on the surface of the flow elswhere.

The rate of cliff recession on The Barrier is notable. Blocks of dacite break loose repeatedly from the upper zone of the cliff during warm dry days in the summer and, tumbling over the precipice, provide a never-ending source of delight for spectators. When, under such circumstances, a high wind blows up Rubble Creek Valley, a pink dust-cloud, visible for miles, may hang over the disintegrating cliff face. On cool foggy days, on the other hand, the rock falls are much less common, and in winter fresh snow may lie completely unscarred at the base of the cliff for at least a day. The recession has continued until the upper part of the cliff-face has attained a slope of about 40 to 50 degrees, but the steepness of the cliff as a whole testifies to its extreme youth.

The present cliff face was first exposed in a recent landslide of major proportions. Judging from the fresh scar on and adjacent to The Barrier, a mass of rock about 1,750 feet across, 1,200 feet from front to rear, and up to 1,200 feet deep, totaling about 50 million tons, fell at this time. The great bulk of the material involved in the slide, judging from the present cliff face and from the debris in the valley below, was derived from the lava lobe, but some underlying masses of black dacite, which are not clearly a part of this lava mass, may have been included. The slide was so sudden that some debris was carried the full length of Rubble Creek Valley,

leaving in its upper part a sheet of coarse material and in its lower part a valley fill of ill-sorted rubble exhibiting a series of elongated mounds, up to 20 feet high, like those of the Javanese slides (Cotton, 1944, pp. 247-252). In Cheakamus Valley the debris spread out as a broad fan which terminated 3½ miles from its source. Vegetation was completely destroyed along the course of the slide and much timber was drowned where drainage was blocked or diverted by the slide. William Downie, who explored Cheakamus Valley in 1858 (British Columbia Archives), reported crossing at this point a wash-out 2½ miles wide on which not a stump remained standing. This part of the slide must have been quickly reforested for 90 years later it was covered by timber sufficiently old and dense to encourage logging operations. It is evident, therefore, that the slide took place not many years before Downie's visit. One old Indian still living in 1947, at Pemberton, B. C., remembered the valley before the slide (Father F. M. Patterson, Lillooet, B. C., personal communication).

A cliff existed at the head of Rubble Creek Valley before the landslide of the middle 1800's, judging from reports of the Indians that they had previously trapped deer at this locality by driving them out to the rim of a cliff. The height and form of this cliff is not known, nor is it absolutely certain that it was the original face of the lava lobe. However, no lava is known to occur in place beyond the limits of the fresh scar on the north side of Rubble Creek Valley even at points 1,300 feet below the top surface of the lobe and only 1,500 feet from the present face of The Barrier. It would appear, therefore, that the original face of the lava lobe rose 1,300 feet above the floor of Rubble Creek Valley in a distance appreciably less than 1,500 feet. It was almost certainly the presence of an unstable rock face of such great height and steepness that led to the landslide of the middle 1800's.

The original appearance of the northwestern face of the third lava lobe is probably duplicated by the cliff at the northern limit of the fourth lobe. This cliff, 1,000 feet high, is no fresh scar like The Barrier but a rock face which has stood long enough to permit a vegetation of lichens and scattered trees to gain foothold on its surface. The piles of talus at its foot are small, though perhaps their predecessors were swept away with the landslide of the past century. The

cliff itself is composed of black glassy dacite in which columnar structure is well developed. The pattern of this jointing is complex, varying abruptly from place to place, but columns with gentle dips seem common. Only at the foot of the cliff, however, can the pattern be clearly deciphered and the irregular surface normal to the columns, and hence roughly parallel to the original cooling surface, reconstructed. This surface suggests more than anything else the forms assumed by wax drippings on the side of a candle, but tens of feet rather than fractions of an inch across, and indicates the former presence of a highly irregular but generally steep and locally overhanging north wall to the dacite mass. The glassy matrix of the dacite here indicates a rapid rate of chilling such as would not be expected if the lobe had solidified as a unit, and suggests instead that the lava accumulated by successive accretions on a precipitous surface. A greater contrast in appearance between the lava of this face and that of the upper surface of the flow could hardly be expected, but microscopic examination shows no significant difference in the two rocks other than in the amount of glass in the groundmass.

DISCUSSION

Those parts of the Clinker Mountain lava flows which came to rest on surfaces above the 4,000-foot level show no significant features to distinguish them from many flows of similar composition elsewhere in the world. Their surfaces are rough but a normal flow pattern can be recognized. Their surface gradients along the axis of the flows vary from 400 to 1,500 feet in a mile, and appreciably steeper slopes are to be found along the levees and margins of the flows though these do not exceed 300 feet in height.

Those parts of the flows which came to rest on surfaces below the 4,000-foot level are clearly anomalous. A steep concave terminal face, almost 1,000 feet high, is to be seen in the Culliton Creek flow where its base lies at about the 3,000-foot level. The third lava lobe on the north side of the northwestern flow, with its base at about the 4,000-foot level, came to rest in the upper part of a deep valley down which it might have flowed with an initial surface gradient in excess of 1,500 feet per mile. Not only did it come to rest at the head of such a steep slope but it accumulated to a depth of 800 feet. And the

fourth lava lobe developed a face which is even now about 1,000 feet high and slopes at an average angle of about 57°. Accretion of successive thin sheets or dribbles of lavas on such a precipitous face may, perhaps, be duplicated on a small scale in modern flows, but hardly in a cliff of this height.

The approximate age of the Clinker Mountain lavas can be inferred from the degree of erosion by Culliton Creek to be not less than several thousand years (pages 556-57). However, the upper surfaces of the flows have not been glaciated nor do they bear erratics; hence the lavas must have been extruded after the disappearance in late Wisconsin times of the Cordilleran ice sheet from the higher altitudes. These two lines of evidence indicate that the lava was laid down either at a very late stage in the recession of this ice sheet, or very shortly thereafter.

Extrusion of lava at the time the dwindling Cordilleran ice sheet still filled the valleys up to about the 4,000-foot level is suggested in explanation of the anomalies described above. Lava coming to rest on higher, ice-free ground would exhibit normal gradients and surface characters. Flows extending to lower levels would, however, come in contact with the ice and abnormal conditions of cooling and solidification would develop.

The mechanism by which lava can be ponded against a large mass of ice is as yet conjectural, but observations made in Okmok Caldera (R. E. Wilcox, personal communication) during the 1945 eruption (Robinson, 1947; Byers *et al.*, 1947), when a stream of lava flowed along the foot of a mass of firn and ice, are helpful in reconstructing the events that may have taken place west of Clinker Mountain. In the Okmok eruption accelerated melting of the ice foot adjacent to the lava flow led to the development of a precipitous and caving ice wall up to about 200 feet high. In this instance the ice provided no barrier to the main lava flow but it may have ponded some smaller streams of lava nearby. The relict mass of the Pleistocene ice sheet occupying the lower ground west of Clinker Mountain could, however, provide an effective dam, for even in its waning stages it blocked the mouths of Rubble and Culliton valleys to depths of 3,000 feet. Lava streams encountering the edge of this frozen barrier would at first, by melting the ice before them, continue their advance, though

only at the expense of much of their heat content (fig. 2). The close approach of hot lava to the ice front and contact between lava and meltwater would be marked by copious amounts of steam, such as was seen at times in the early stages of the Okmok eruption, and would lead to a more rapid dissipation of heat than prevailed when the lava flowed across dry ground. Melting at the foot of the ice wall and caving of great slabs outward onto the lava might further accelerate cooling by providing a large area of contact between ice and heated rock. In time a solid and presumably steep-sided skin or wall of lava would be developed against the ice face, separating this from the molten material upstream. Heat radiated from this solid, though still warm, mass of lava would cause continued melting of the ice face, and any open space created this way might or might not become occupied by meltwater. During the earlier parts of the eruption this lava dam might be broken or overwhelmed by the mass of molten rock behind it; later, however, as the main stream became cooler and more viscous, the solid lava wall could persist and the stiff magma might become banked up to a considerable height above the dam without exerting the pressure necessary to cause its failure. Local threads of fluid lava might, nonetheless, break over or through the lava dam, and, on entering space between it and the ice, congeal as relatively small sheets or dribbles like those seen on the north face of the fourth lava lobe (page 561) and on The Table (Mathews, 1951b). Although the ice front would be extensively modified by melting and caving, its broader outlines might persist and impart to the lava walls certain irregularities in form which would not have been developed in the absence of ice. Such features as the concave terminus of the Culliton Creek flow may, for example, have originated as a cast of a convex ice front. The unduly high and steep face of both this flow and the fourth lava lobe may likewise be attributed to moulding against a steep, or even precipitous, ice front. Pressure of the ice or of impounded meltwater against the steep lava front might be sufficient to prevent its collapse after cooling and fracturing had taken place. With the disappearance of the ice, however, the steep faces would be potentially unstable and liable, sooner or later, to fall in one or more enormous landslides, like the one which so recently exposed The Barrier. It would seem, then, that

the major anomalies of the Clinker Mountain flows, so difficult to account for in the absence of ice, are readily explained by the hypothesis that the advance of the lavas was impeded at several places along the margins of the dwindling Pleistocene ice sheet.

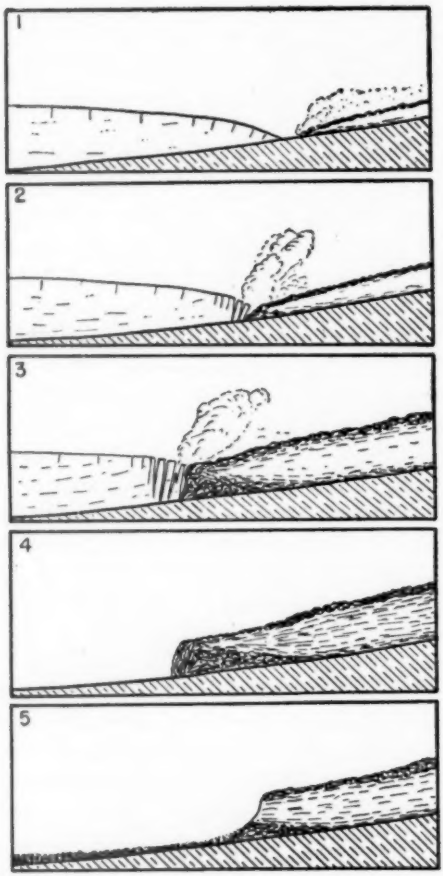

Fig. 2. Conjectural history of an ice-dammed lava flow.

1. First approach of lava (right) to the ice (left). Relatively rapid advance of the flow probably accompanied by only minor emission of steam from the magma or generated from small amounts of water on the ice-free ground.

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Fig. 2 (cont.)

2. Continued advance of lava, though at a slower rate, onto ground previously covered by ice. Increased emission of steam developed by direct contact of lava with meltwater, with fallen blocks of ice, or with the main ice wall. Rapid chilling of magma at the flow terminus leading to development of low, temporary lava dams.

3. Overriding by the main lava stream across the earliest dams followed by the development of an effective dam when the bulk of the lava upstream becomes stiffer. Local threads of fluid lava may break out and overflow into the gap between the lava front and the ice wall to cool and solidify as accretions.

4. Disappearance of the ice, exposing the steep terminal face of the main flow and the coating of accretions. (Fourth lava lobe, page 561.)

5. Collapse of the terminal face, exposing the interior of the flow. (The Barrier.)

[American Journal of Science, Vol. 250, August 1952, Pp. 566-585]

SOLUTION DEPRESSIONS IN DIORITE IN NORTH CAROLINA*

H. E. LeGRAND

ABSTRACT. During 1950 more than 40 enclosed depressions, resembling sinks of limestone terranes, were observed by the writer in the igneous rocks of the Piedmont plateau of North Carolina. These depressions, averaging about 200 feet in diameter and about 3 feet in depth below the lowest possible overflow point, are restricted to upland areas of dioritic rocks.

That the agents of subaerial erosion are apparently incapable of forming these enclosed depressions suggests that ground water is the principal agent in forming them. The evidence indicates that soluble rocks underlie the depressions, that an appreciable amount of dissolved mineral matter is extracted from the dioritic rocks by ground water, and that surface subsidence is a consequence. More than three times as much mineral matter is extracted by circulating ground water from diorite as from granite, the most common rock of the Piedmont.

Solution subsidence is not confined to the enclosed depressions but is even more active in valley heads where the ground water circulation and the consequent solution are greater. Studies in the Piedmont of the occurrence and movement of ground water and an appraisal of data on the quantity and chemical quality of natural water reveal that ground water is a more significant agent in the erosion of igneous rocks than is generally believed.

INTRODUCTION

WHILE studying the ground water in a part of the Piedmont in North Carolina during the summer of 1950, as a part of investigations being made under a cooperative agreement between the U. S. Geological Survey and the North Carolina Division of Mineral Resources, the writer noticed several enclosed depressions in the upland areas. Since that time, as a result of casual observation rather than systematic search, he has seen more than 40 similar depressions in the Piedmont area of the state. They are similar in appearance to sinks in limestone, although those described are restricted to plutonic rocks of intermediate composition where limestone is absent.

The depressions are irregularly circular. A few are slightly elongated, the long axis of the depression being roughly in line with the nearest surface drainageway and appearing to be the discontinuous headward extension of it. The depressions range in diameter from about 100 feet to more than 300 feet,

* Publication authorized by the Director, U. S. Geological Survey.

the average being about 200 feet. They range in depth below the lowest possible overflow point from a few inches to about 6 feet, averaging nearly 3 feet. More than a dozen depressions are at least 3 feet deep. The inner slopes are not steep but are typical of those of the upland areas. Rock is nowhere exposed in the depressions. A topographic sketch of a depression on the Ford property, 2 miles north of Cleveland, Rowan County, is shown in figure 1. Most of the depressions in Rowan County cannot be seen on the aerial photographs examined; however, photographs made during the late winter, when water is reported to accumulate in them, may reveal their presence. Despite moderately heavy rains of summer, infiltration of precipitation is generally rapid enough to allow the growth of crops within the depressions. Attempts have been made in several cases to drain them. For example, on the Misenheimer farm 5 miles southeast of Cleveland, Rowan County, a ditch several feet deep was excavated to drain a large depression.

The depressions are in nearly flat upland areas underlain by intrusive rocks of intermediate composition. They are found in one or more extensive areas of diorite or gabbro-diorite in each of the following counties in North Carolina: Rowan,

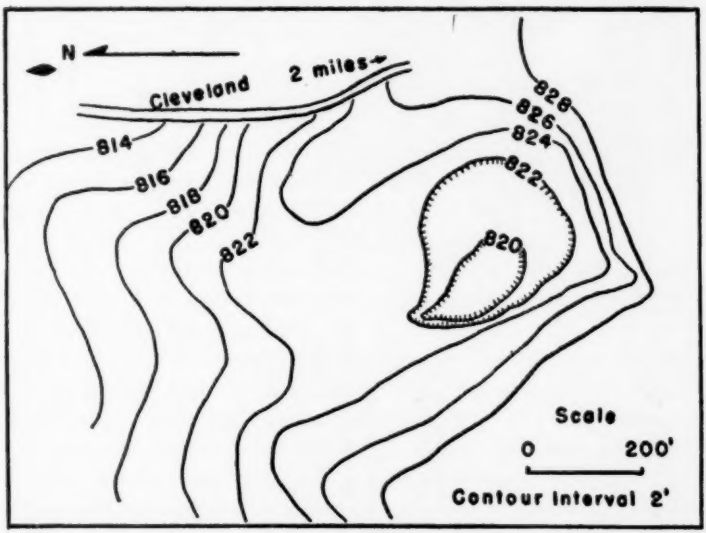

Fig. 1. Topographic map of a depression on the Ford property, 2 miles north of Cleveland, Rowan County.

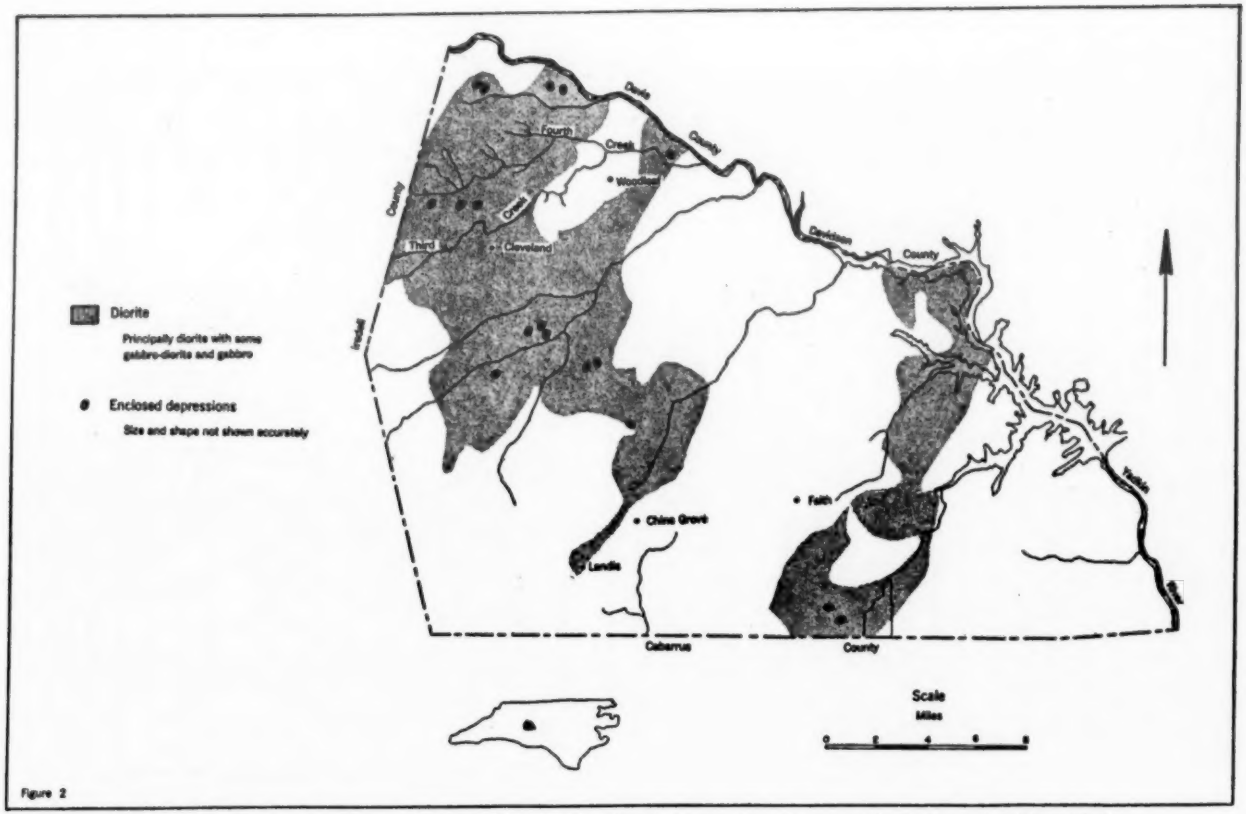

Fig. 2. Map of Rowan County showing relation of enclosed depressions to areas of diorite and gabbro-diorite.

Davidson, Cabarrus, Iredell, and Alamance. Figure 2 shows the location of many of the depressions in Rowan County.

Although the depressions have been recognized by the owners of the tracts of land on which they are situated, they apparently have received no attention scientifically. So far as genesis is concerned they are abnormal land forms on igneous rocks; the normal destructive processes depend on running surface water, producing fully drained, rather than enclosed, depressions wherever slopes converge. The apparent inability of subaerial erosion to account for the depressions (erosion by wind action seems quite out of the question) requires that consideration be given to ground water as an agent that causes subsidence of the land surface through solution. To test the hypothesis of solution subsidence it is necessary to show that soluble rocks occur beneath the depressions, that appreciable mineral matter in solution is extracted from the rocks, and that there is subsidence of the surface as a consequence. The requirements needed to satisfy this hypothesis are discussed in the following pages.

PHYSIOGRAPHY

All depressions noted in the present study are on the Piedmont plateau, or Piedmont as it is generally called. It is a plain so thoroughly dissected by streams that its plainlike features are noticeable only by comparing the tops of interstream areas. The drainage is of fine texture, and consequently an undulating or hill-and-valley type of topography prevails. The larger streams flow southeast in consequence of the regional slope. Many tributaries flow northeast or southwest, parallel with the most prominent rock structures; some of those streams are controlled by structure, whereas others merely follow the most direct surface slope which coincidentally is parallel with the structure.

The depressions most thoroughly studied are in northwestern Rowan County in an area of almost typical Piedmont topography. The depressions are in nearly flat but narrow upland areas where the local relief is about 100 feet. In addition to the depressions there are slight undulations on the uplands which appear to follow no particular pattern, and in this respect the local topography is not typical of that in the Piedmont. In fact, the local topography on the nearly flat

uplands resembles that on many limestone terranes. Many small springs flow from the valleys which form reentrants into the upland areas.

SUMMARY OF GEOLOGY

The geology of the areas where depressions occur is imperfectly known. Many depressions occur in Rowan County, where the writer had previously made a reconnaissance geologic map in connection with systematic ground water studies. The geologic map of Rowan County prepared by the writer is shown as figure 3 and the geology of the county is described briefly below. The extreme eastern part of Rowan County is underlain by slates and volcanic rocks. Depressions do not occur in them, and they need not be discussed further. The remainder of the county is underlain chiefly by felsic to mafic plutonic rocks, predominantly granite, diorite and gabbro-diorite. In some places the diorite and gabbro-diorite show a northeast structural trend. Homogeneous masses of both granite and diorite are found, although for the most part these two types of rocks are profusely interlayered or interpenetrated. The subordinate rock, which may be granite in one place and diorite in another place, appears to vein the predominant rock, so that changes in rock type generally occur every few feet. Although the individual rock bodies are generally not gradational, the predominance of diorite in one place and granite in another is a gradational feature. The intrusive complex of granite and diorite is the most outstanding feature of the geology.

Neither the age nor the age relationship of the rocks is clearly known; all are of Paleozoic age or older.

In the field study, special attention was paid to the diorite in order to determine its relation to the depressions. Almost nowhere is the diorite free of granitic bodies, although in the area mapped as diorite less than 5 per cent of the aggregate rock appears to be granitic. The diorite varies in composition from place to place, the most mafic varieties actually being gabbro. Watson and Laney (1906, p. 20), who examined thin-sections of the diorite from several places in western Rowan County, say that the diorite is composed largely of hornblende and plagioclase feldspar, the typical accessory minerals occurring in very subordinate amounts.

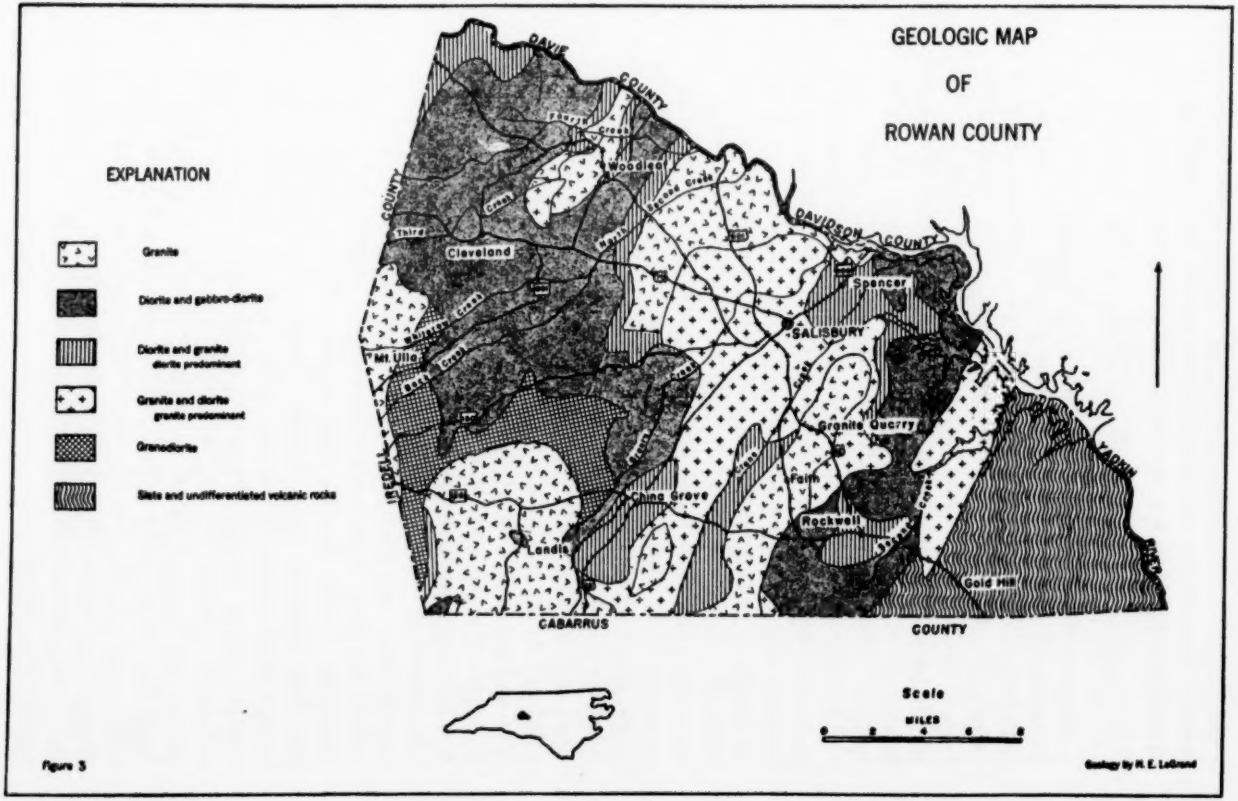
GEOLOGIC MAP
OF
ROWAN COUNTY
EXPLANATION
Granite
Diorite and gabbro-diorite
Diorite and granite
diorite predominant
Granite and diorite
granite predominant
Granodiorite
Slate and undifferentiated volcanic rocks
DAVIE COUNTY
IREDELL COUNTY
DAVIDSON COUNTY
CABARRUS COUNTY
Cleveland
Woodleaf
Mt. Ulla
China Grove
Landis
SALISBURY
Spencer
Granite Quarry
Rockwell
Gold Hill
Faith
Scale
MILES
Figure 3
Geology by H. E. LeGrand

Fig. 3

That depressions do not occur in rocks higher in silica content than diorite indicates that the chemical composition of the underlying rock is a factor in their development.

OCCURRENCE AND MOVEMENT OF WATER IN THE PIEDMONT

Despite intensive studies of the physiography of limestone terranes, there is a prevailing disagreement concerning the sequence of events that lead to solution subsidence. This is largely due to a general lack of attention to the basic principles of the occurrence and movement of ground water and the effects these principles have on land forms. To understand the extraction of mineral matter, whether from limestone or igneous terranes, requires consideration of ground water behavior.

The igneous rocks of the Piedmont are commonly mantled by 10 to 50 feet of soil and weathered rock in which water occurs between the individual mineral particles. In sharp contrast is the occurrence of water in the underlying bedrock, where water is restricted to fractures. These fractures are generally not evenly distributed, so that they may be an inch or two or several feet apart. Many are interconnected sufficiently to allow ground water to circulate through them. In many places fracture openings are only a fraction of an inch wide, although there is a great variation in size of openings. In so far as the yields of water wells indicate the degree of fracturing, the size and number of fractures appear to decrease with depth, at a rate that appears to be approximately logarithmic. As a result, most ground water occurs at a depth of less than 125 feet—much of it within the uppermost 30 feet of the bedrock—and perhaps less than 5 per cent of the ground water occurs below 175 feet. Hence, the lower limit of the underground reservoir is not a sharp boundary but a thick, indefinite zone; the top, however, is a definite though fluctuating surface known as the water table. The water table is absent in a few places because of the absence of fractures, but it is present almost everywhere. The water table lies in the residuum in some places and in the bedrock in other places. It is generally at least 30 feet below the surface beneath the uplands. The water table stands higher beneath the upland areas than beneath the adjacent valleys, although it lies farthest below the land surface in the uplands; in other words, it slopes much like the land surface but less steeply.

Water is discharged from the underground reservoir as seeps and springs which produce the base flow of streams, and by evaporation and transpiration. Evaporation and transpiration are not pertinent to solution subsidence because they are not considered capable of transporting mineral matter to any degree, they are not localized to depressions, and they operate largely in the residuum where most soluble material has already been removed. A spring occurs at a point of convergence of the surface slope and water table, generally at the base of a steep valley head. The flow of a spring is dependent on the amount of water supplied by precipitation and subsequent infiltration, on the topography, and on the ability of the rocks to transmit water underground to the spring. More than 45 inches of precipitation distributed rather evenly throughout the year recharges the underground reservoir and thus prevents its depletion. After each rainy period the water table beneath the uplands rises, steepening the hydraulic gradient and thereby increasing the flow of springs.

After infiltrating downward through the residuum, as a relatively continuous body or sheet, water circulating in the bedrock is restricted to fractures. Most of the natural circulation is confined to a zone extending no lower than the upper 30 feet of bedrock because the number and size of water-bearing fractures below that zone decrease greatly. Unlike homogeneous and isotropic water-bearing rocks in which much water moves at considerable depth below the level to which it ultimately rises to discharge, the igneous rocks of the Piedmont constrict the downward movement of water and shunt it laterally to discharge points above the base of the perennial streams. Thus, the movement of ground water in the Piedmont from the recharge or interstream areas to the discharge or stream areas follows in general an almost direct path, although locally, of course, the water flows through devious interconnecting fractures. Evidence that most of the circulation takes place near the top of the bedrock is found in the facts that the yields from deep wells are not appreciably greater than the yields from shallow wells and that, with few exceptions, there is no significant difference in temperature in water from wells of various depths. If, in the average deep well, a substantial part of the water came from the lower part of the hole, its temperature and the average temperature of all the

water from the well would be higher than that from shallower wells, which is not the case.

In terms of the water table, the greatest circulation at any given place occurs in the zone between its highest and lowest stages, the circulation being most active just below the water table at all times. From the direct relation which appears to exist between circulation and solution it can be concluded that the greatest solution is in this zone. From studies of ground water in the limestones of Florida, Stringfield[1] reached a similar conclusion—that the greatest solution occurs in the zone between the highest and lowest stages of the water level.

REMOVAL OF MINERAL MATTER IN SOLUTION

A part of the systematic study of ground water in the igneous and metamorphic rocks in North Carolina deals with chemical character of water discharged from these rocks. Some of the analyses that have been made are given in the accompanying tables. These analyses show clearly that the rocks are somewhat soluble, as pointed out in general terms by Clarke (1924, p. 484):

> "The evidence, both as found by experiment in the laboratory and by field observations, shows that practically all minerals, certainly all of the important ones, are attacked by water and carbonic acid. The pyroxenes and amphiboles yield most readily to waters, then follow the plagioclase feldspars, then orthoclase and the micas, with muscovite the most resistant of all. Even quartz is not quite insoluble . . ."

The total amount of mineral matter dissolved and later discharged by ground water depends on the length of time water is in contact with the soluble rock and on the solubility of the mineral constituents. The amount of dissolved mineral matter in water contained in the rocks increases with time of contact, although this is not a simple relation. Other factors being equal, the rate of increase in mineral content of water contained in a rock appears to lessen with approximately logarithmic regression as time passes. Thus, if water is in contact with a soluble rock long enough it will become

[1] Stringfield, V. T., oral communication, 1947.

saturated with dissolved mineral solids, and the water will be powerless to extract more mineral matter from the rock. It follows that stagnant water is not an important solutional agent. Circulating ground water, on the other hand, is important because water laden with mineral matter moves out of the rocks and water containing little or no mineral matter moves in to replace it. Thus, mineral matter is continuously being extracted from the rocks. Many of the rocks of the Piedmont show no great variation in degree of fracturing, so that there appears to be a nearly equal rate of circulation of water through each type of rock; however, the circulation seems to be slower at depth, as would be expected, so that the water is in contact with the rocks for a longer period and the mineral content of water from deep wells is higher than that in water from shallow wells. If the water level in the deep wells is lowered considerably by pumping the mineral content of the water appears to increase. This, too, can be expected because it means that water is being drawn from depth in greater quantities than if the water level were lowered only slightly.

Where the circulation of water in different kinds of rock is equal, the chemical quality of the water reveals the general solubility of the source rock.

Table 1 shows the chemical quality of some well waters derived from rocks in the environs of the depressions. Not all features of the analyses can be explained easily. Nevertheless, it is evident that the amount of dissolved solids in water from diorite is three or four times greater than that in water from granite. In fact, the diorite contains water which, except for a higher silica content, is comparable in dissolved solids and mineral constituents to many waters in limestone in the Atlantic Coastal Plain.

Table 1 also shows the character of water from four wells tapping residual material above bedrock. That none of these contained more than 50 parts per million of dissolved solids indicates that solution is more active in bedrock than in the residual material.

The quality of spring water also reveals the solubility of the source rock, but to a lesser extent than well water. Many spring waters flowing partly or entirely through residuum have very little mineral matter, whereas other spring waters

TABLE 1

Analyses of water from selected wells in the Piedmont area of North Carolina

Analyzed by the U. S. Geological Survey

Parts per million

County	Location	Owner	Silica SiO_2	Iron Fe	Calcium Ca	Magnesium Mg	Sodium & potassium Na+K	Bicarbonate HCO_3	Sulfate SO_4	Chloride F	Fluoride F	Nitrate NO_3	Dissolved solids	Total hardness as $CaCO_3$	Depth of well (feet)	Geologic source
Rowan	Kannapolis	T. H. Powers	24	0.14	4.1	1.5	4.0	24	1.6	2.2	0.0	0.9	52	16	161	Granite
Rowan	Rockwell	Town of Rockwell	27	.09	9.1	1.4	7.0	48	1.7	1.6	.1	.2	71	28	144	Granite
Rowan	Landis	Town of Landis	37	.40	9.4	.6	12	54	3.6	2.2	.2	.1	92	26	406	Granite
Cabarrus	Kannapolis	Ben Aycock	27	.03	4.3	.9	5.2	26	.9	2.0	.0	.8	58	14	180	Granite
Cabarrus	Kannapolis	J. G. Love	..	...	...	...	...	44	...	...	...	...	...	24	160	Granite
Cabarrus	Kannapolis	S. W. Cline	..	...	...	...	...	20	4	10	.1	...	...	26	...	Syenite
Cabarrus	Concord	Cannon Mlils	..	...	...	...	...	216	36	128	.3	...	...	279	612	Granite and diorite
Cabarrus	Concord	Odell School	..	...	...	...	...	90	2	5	.1	...	...	63	200	Granite and diorite
Rowan	Landis	Town of Landis	23	.06	54	2.0	17	100	86	2.5	2.2	.1	246	143	604	Granite and diorite
Rowan	Landis	Town of Landis	35	1.6	37	1.7	9.9	63	59	2.8	.6	2.7	185	99	1009	Granite and diorite
Cabarrus	Concord	City of Concord	..	.22	...	...	...	270	26	24	.2	...	...	258	135	Diorite
Rowan	Landis	Town of Landis	31	.49	174	3.5	15	82	391	2	1.8	.2	696	449	1108	Diorite

TABLE 1 (Cont.)

Analyses of water from selected wells in the Piedmont area of North Carolina

Analyzed by the U. S. Geological Survey

Parts per million

County	Location	Owner	Silica SiO_2	Iron Fe	Calcium Ca	Magnesium Mg	Sodium & potassium Na+K	Bicarbonate HCO_3	Sulfate SO_4	Chloride F	Fluoride F	Nitrate NO_3	Dissolved solids	Total hardness as $CaCO_3$	Depth of well (feet)	Geologic source
Rowan	China Grove	Town of China Grove	26	.21	47	4.9	11	111	63	2.5	.2	.0	219	137	714	Diorite
Rowan	China Grove	Town of China Grove	30	.17	57	5.4	12	103	98	3.2	.1	.3	268	164	319	Diorite
Rowan	China Grove	Town of China Grove	35	.06	57	5.3	13	123	84	2.5	.3	.1	259	164	750	Diorite
Rowan	Cleveland	Town of Cleveland	47	.30	38	16	9.5	127	23	25	.1	22	260	161	187	Diorite
Cabarrus	Roberta	Roberta Mfg. Co.	51	.80	53	21	17	146	103	19	.3	1.6	366	219	276	Gabbro-diorite
Rowan	1 mi. S. of Cooleemee	T. C. Hendrix	50	.20	23	11	8.1	87	26	12	.2	5.5	191	103	49	Gabbro-diorite
Rowan	2 mi. N. of Cleveland	Ira Hodge	..	...	...	...	...	...	...	...	...	...	30	13	45	Residuum of diorite
Rowan	2 mi. N. of Cleveland	Ross Wood	..	...	...	...	...	...	...	...	...	...	50	22	40	Residuum of diorite
Rutherford	.....	Alexander Mfg. Co.	13	.10	3.3	1.7	3.8	13	1.4	6.8	.1	2.0	41	15	25	Residuum of mica schist
Rutherford	.....	Alexander Mfg. Co.	12	.11	2.6	1.6	3.2	18	1.2	1.8	.1	1.7	32	13	25	Residuum of mica schist

circulate through granite or other relatively insoluble rocks yet are high in mineral content, showing that the circulation is slow. Spring waters generally circulate more rapidly through the rocks than do well waters, and, consequently, the dissolved-solid content of spring waters is considerably less than that of well waters.

It can be seen from table 2 that springs emerging from diorite near the depressions have more dissolved solids than the average of the springs listed. In a report[2] on some mineral springs in the state, the mean dissolved-solids content of water from 22 springs in the Piedmont was 150 parts per million. The average flow of these springs was only 1.0 gallon a minute, suggesting that their high mineral content may be owing, in part, to poor circulation of water through the rocks. The majority of these springs, selected for their mineral properties, are not typical. Of the thousands of springs in the Piedmont of North Carolina, the median concentration of dissolved solids is probably less than 45 parts per million.

The geologic source of water from large streams is obscured, owing to the mixture of water flowing over and through diverse rocks. On the other hand, the mineral content of water from a short stream may reveal much information on the geology of its small drainage area.

Table 3 shows miscellaneous analyses of water from some small streams in the Piedmont. Those which have diorite as the principal source rock drain the areas in which some depressions occur. In evaluating these analyses it should be noted that the concentration of mineral matter in a stream appears to vary inversely with the amount of its flow, so that an analysis made after a heavy rain will show less mineral matter than one made at the same place after a long period of fair weather. Samples for analysis were collected at different times, and consequently the relative stage of concentration of mineral matter was not the same for each analysis. Nevertheless, according to table 3 the dissolved solids in water flowing from diorite are considerably higher than that of water from granite, indicating that considerable mineral matter is being removed from diorite in drainage areas underlain by it.

[2] North Carolina Geol. and Econ. Survey, Econ. Paper 15, 1908.

TABLE 2

Analyses of water from selected springs in the Piedmont area of North Carolina

Analyzed by the U. S. Geological Survey

Parts per million

County	Location	Owner	Silica SiO_2	Iron Fe	Calcium Ca	Magnesium Mg	Sodium & potassium Na+K	Bicarbonate HCO_3	Sulfate SO_4	Chloride F	Fluoride F	Nitrate NO_3	Dissolved solids	Total hardness as $CaCO_3$	Yield (gal. per min.)	Geologic source
Gaston	2 mi. N. of Lowell at edge of road near Catawba River	.....	23	0.21	4.9	2.2	5.3	31	4.3	1.9	0.0	0.2	59	21	½	Hornblende gneiss
Rowan	2 mi. N. of Cleveland	Ross Wood	..	....	...	...	...	...	...	...	...	...	74	34	2	Diorite
Rowan	2 mi. N. of Cleveland	Ira Hodge	..	....	...	...	...	...	...	...	...	...	89	39	1	Diorite
Cleveland	4 mi. W. of Shelby	T. P. Hamrick	11	.09	1.7	.9	3.5	11	1.2	2.2	.1	2.4	30	8	15	Granite and mica schist
Rutherford	.....	Grady Withrow	15	.34	2.0	1.0	3.8	17	1.6	1.2	.0	.0	33	9	4	Granite gneiss
Stokes	Lawsonville County School	.....	..	.04	...	...	...	13	2	2	...	...	...	12	5	Granite gneiss

TABLE 3

Analyses of water from selected streams in the Piedmont area of North Carolina

Analyzed by the U. S. Geological Survey

Parts per million

	Silica SiO_2	Iron Fe	Calcium Ca	Magnesium Mg	Sodium & potassium Na+K	Bicarbonate HCO_3	Sulfate SO_4	Chloride F	Fluoride F	Nitrate NO_3	Dissolved solids	Total hardness as $CaCO_3$	Date of collection	Geologic source
1. Forbush Creek near Yadkinville, at gage	13	0.04	3.1	1.3	4.3	22	2.0	1.4	0.0	0.3	37	13	8/11/44	Granite gneiss
2. Indian Creek at Crouse (Catawba Basin)	13	.04	3.2	1.3	3.7	19	2.1	2.1	.1	.5	36	13	8/10/49	Granite
3. Small creek in Rowan County, 2 mi. S. of Faith; ½ mi. N. of N. C. Route 152	..	....	...	...	...	...	...	...	...	...	71	20	10/12,50	Granite
4. Fourth Creek near Statesville	16	.5	5.4	1.6	2.6	19	1.9	4.8	...	.3	52	20	1/11/26	Granite gneiss
5. Davidson Creek near Cornelius (Catawba Basin)	26	.10	8.4	4.3	4.0	50	2.2	2.6	.1	.2	76	39	9/23/49	Granite and diorite
6. Abbotts Creek at Lexington, at gage	20	.02	9.9	3.4	19	59	5.8	18	.2	.8	109	39	8/12/44	Diorite and granite
7. Third Creek at Cleveland, at gage	20	.02	6.4	2.7	19	40	4.0	22	.1	.5	98	27	8/11/44	.....
8. Third Creek, in Iredell County, on county road 1¼ mi. W. of Rowan County line and 2¼ mi. N. of Amity Hill	..	....	...	...	...	...	...	...	...	...	66	23	10/12/50	Predominantly granite — some hornblende gneiss

TABLE 8 (Cont.)

Analyses of water from selected streams in the Piedmont area of North Carolina

Analyzed by the U. S. Geological Survey

Parts per million

	Silica SiO_2	Iron Fe	Calcium Ca	Magnesium Mg	Sodium & potassium Na+K	Bicarbonate HCO_3	Sulfate SO_4	Chloride F	Fluoride F	Nitrate NO_3	Dissolved solids	Total hardness as $CaCO_3$	Date of collection	Geologic source
9. Third Creek at Cleveland, at gage	..	....	...	...	...	...	...	...	...	...	76	27	10/12/50	Granite, hornblende gneiss, and diorite
10. Small unnamed creek in Rowan County, ½ mi. south of Fourth Creek, 3 mi. N. of Cleveland	..	....	...	...	...	...	...	...	...	...	132	70	8/16/50	Diorite
11. Small unnamed creek in Rowan County, 1 mi. N. of 4th Creek, 3¼ mi. NW. of Woodleaf	..	....	...	...	...	...	...	...	...	...	134	76	10/12/50	Diorite
12. Small unnamed creek in Rowan Co., 2 mi. W. of its junction with S. Yadkin River and 3¾ mi. NW. of Woodleaf	..	....	..	...	...	...	...	...	...	...	140	77	10/12/50	Diorite
13.* Hypothetical stream in the Piedmont of North Carolina	16	0.81	5.2	1.9	5.2	1.9	5.9	4.6	...	0.8	62	20	.....	.....

* Represents average (mean) of 38 analyses of streams in the Piedmont of North Carolina, published in Preliminary report on the chemical quality of the surface waters of North Carolina, with relation to industrial use: North Carolina Dept. Cons. and Devel. Econ. Paper 61, p. 43, 1925.

The tables of chemical analyses show the concentration of mineral matter in waters of the Piedmont and the relative solubility of the source rocks. More pertinent than the mineral concentration of one or a large number of samples of water is the total mineral matter extracted by water from the rocks in a given time and area. This can be calculated if both quality and quantity of water discharged from the drainage areas are known.

Records of the quantity and quality of surface water compiled by the U. S. Geological Survey are chiefly for large drainage areas, the waters of which come from different types of rocks. The chemical character and amount of water yielded in a given area underlain entirely by a single rock type are not known, and consequently accurate calculations of the total amount of dissolved mineral matter removed from the environs of the depressions in diorite cannot yet be made. However, some speculation is worthwhile.

Drainage from the area of depressions in northwest Rowan County is largely into Third and Fourth Creeks. Some records are available for Third Creek at the gaging station about 2 miles north of Cleveland. On August 11, 1944, the dissolved-solid content of Third Creek was 98 parts per million. The discharge was 37 cubic feet per second, or 27 cubic feet below the yearly mean. The flow for that day, which was preceded by a long interval of nearly fair weather,[3] consisted entirely of discharge from the underground reservoir. About 20,000 pounds or 114 cubic feet of mineral matter, assuming an average specific gravity of 2.75, was extracted in solution in the 87-square-mile drainage area during the 24 hours of August 11, or 1.3 cubic feet per square mile.

Because the daily mean discharge is greater, the daily mean extraction of mineral matter should be greater, though not in direct proportion to the increase in discharge. The upper three-quarters of the drainage area is underlain chiefly by granitic rocks, which supply much less dissolved mineral matter than the diorite. Thus the amount of mineral matter taken from the diorite is conservatively estimated as twice

[3] According to the U. S. Weather Bureau, 0.68 inch of rain occurred at the Salisbury station, Rowan County, during the first 11 days of August, of which 0.36 inch came on the 1st and 2nd days of the month and the remaining 0.32 on the 7th and 8th.

that of the average for the entire basin area, or about 2.7 cubic feet per square mile per day, or about 1,000 cubic feet per square mile per year. The removal of dissolved mineral matter is not equal in all parts of an area, even where the same rock prevails. It is greatest in the vicinity of, and up gradient from, springs or other discharge points, where circulation is greatest. The proximity of springs to the depressions and the steep hydraulic gradient from depressions toward springs indicate that circulation and consequent solution are great in the depression areas.

An estimate can be made of the rate of enlargement of a depression. The depression on the Ford property, for example, receives about 2,300,000 cubic feet of precipitation annually in its 620,000 square feet of internal drainage area. Within this area probably at least half the total precipitation infiltrates into the ground to become ground water. Although the mineral content of water discharged from the diorite may be several times greater, it is assumed that about 30 parts per million of the total dissolved-solids content of the water represent mineral matter dissolved from the diorite in the enclosed depression. Thus, it is estimated that about 13 cubic feet of rock is dissolved away each year in the Ford depression. In the enclosed depressions, the rate of solution should be almost directly proportional to the size of the internal drainage area. Hence, the rate of solution beneath small depressions is probably not as great as that beneath larger depressions. Solutions in the heads of valleys having large drainage areas is thought to be of considerable magnitude.

Plenty of time exists for the formation of the depressions, so long as the normal processes of subaerial erosion do not cause valleys to extend headward to them, in which case parts of the rims are lowered and the depressions become normal valley heads. Unquestionably many enclosed depressions are being destroyed by the headward extension of valleys. Some are destroyed before they reach a mature stage of development. However, many depressions situated on divides may escape destruction by subaerial erosion for thousands of years.

SURFACE SUBSIDENCE

In limestone terranes the removal of dissolved mineral matter creating voids does not necessarily lead to subsidence of the

overlying rock and residual material. However, if caverns occur near the surface in the upper part of bedrock their roofs may collapse and the effect of this slumping may be observed at the surface. Ground water studies clearly indicate that, in the igneous rock of the Piedmont, mineral matter is dissolved largely in the upper part of the bedrock, but they do not reveal the nature of the voids produced. Data on wells in rocks of the Piedmont fail to show the presence of large air-filled or water-filled caverns, such as are found in some limestone terranes; however, many wells penetrate a zone of soft clay beneath a zone of bedrock, and it is possible that this clay may have moved downward through sizable openings; it is also possible that this clay represents the insoluble residue resulting from solution in this zone. Does removal of dissolved mineral solids occur at the top of bedrock, and minute but constant subsidence occur concomitantly? Water moving downward through the residuum reaches the top of the impervious bedrock where it is shunted down slope to fractures, which transmit it deeper into the rock or farther down the bedrock slope to surface discharge points. That much of the ground water discharge occurs at the contact between residuum and bedrock suggests that solution and, consequently, some subsidence occur in this zone. Whatever the nature of the voids produced, it is evident that solution occurs largely at, or near, the top of bedrock, where subsidence also is possible.

CONCLUSIONS

Depressions occur in the Piedmont of North Carolina in nearly flat upland areas of diorite. The relatively high solubility of these rocks, which appear to yield more than three times as much mineral matter to solution than does granite, is considered to be the cause of surface subsidence producing the depressions. The solubility of the rock and the degree of circulation of ground water through it are the factors that largely govern solution. Depressions develop on nearly flat interstream areas which so far have escaped the channel type of subaerial erosion, so active on adjacent slopes.

The greatest circulation and consequently the greatest solution occur near springs and along the steepest parts of the hydraulic gradient above them; in terms of surface topography this is in the steep headward parts of valleys. Although sur-

face subsidence forming depressions is not noticeable on these slopes, there are numerous bulbous valley heads similar to depressions except that they have a surficial drainage outlet. Many of these valley heads are considered to have been formed in part by solution subsidence. Despite the lack of recognition by geologists of the role of solution in the production of land forms on igneous and metamorphic rocks, the evidence afforded by a study of the quantity and quality of our natural waters indicates that ground water is removing enough dissolved mineral matter in many places to alter the topography. Although running surface water is by far the dominant agent in carving landscapes in the southeastern Appalachian Piedmont, the circulation and discharge of ground water containing mineral matter in solution appears to constitute an important agent in the headward migration of valleys and the initiation of many slopes. By giving due consideration to subterranean as well as subaerial erosional processes, a more complete understanding can be reached of the sequence of events leading to a certain stage of degradation in igneous and metamorphic terranes.

The removal of dissolved mineral matter from the rocks, especially in valley heads, has resulted in the enlargement of fractures or voids through which circulating ground water moves relatively freely. The productivity of wells in the Piedmont, which is generally greater in valley heads than in any other topographic location (Mundorff, 1948, p. 31), supports this deduction, although several other factors enter into the productivity of wells.

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A GRAPHIC TESTING PROCEDURE FOR POINT DIAGRAMS

INGEMAR LARSSON

ABSTRACT. A graphic test is described as a means of showing the change in distribution of petrofabric or other data plotted on the Schmidt net with increasing number of measurements.

CHAYES (1949) gives in *Structural Petrology of Deformed Rocks* (Fairbairn, 1949) a discussion of the collection and statistical treatment of the analysis of three-dimensional fabric diagrams. He shows in several tests the possibility of getting a statistical significance for theories built on petrofabric data. Also Pincus (1951) discusses statistical analysis of the data of point diagrams. By using the methods discussed by these authors, it is possible to get a mathematical estimation of the amount of security in conclusions collected from petrofabric data.

For practical geological work the present author has tried a graphic method of control for petrofabric work. The amount of security is here only visually controlled by the changeability of curves representing different numbers of measurements. The author is conscious of the fact that by this graphic method the security cannot be exactly estimated, but for many problems the exactitude reached by this graphic method is sufficient.

The method is being employed on petrofabric work in a coastal gneiss in Blekinge, southern Sweden. Thin sections are made perpendicular to B-axis, and biotite diagrams are plotted on the Schmidt net after Sander (1930, 1948 and 1950). The idea

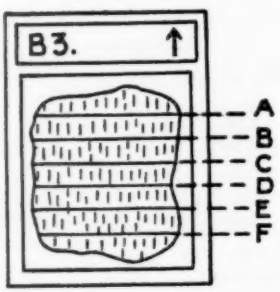

Fig. 1. Biotite poles in the rock-fabric are measured along parallel lines perpendicular to anisotropy. For each line a part-diagram is plotted.

of the method is to see if the distribution of the position of crystals plotted on the diagram changes with increasing number of measurements.

The poles of the biotite crystals (perpendiculars to (001)) are measured in the fabric along lines, each representing a zone visible in the microscope (fig. 1). The poles measured along each line are plotted in one diagram. The measuring lines are all parallel, equally spaced, and perpendicular to possible anisotropy.

Now the problem rises if the distribution of the position of poles in the first part-diagram A is the same as in the first and the second together, A+B, or as in A+B+C and so on. To investigate that, the distribution of the position of poles by this graphic method is represented by curves. One curve for part-diagram A = the distribution of 59 biotite poles, one for part-diagrams A+B = 112 poles, one for A+B+C = 165 poles and so on. The investigation runs as follows.

After plotting the biotite poles on the diagram it is divided into 18 sectors, 20 degrees in each (fig. 2). The poles in each sector are counted. The numbers are put into a table where the

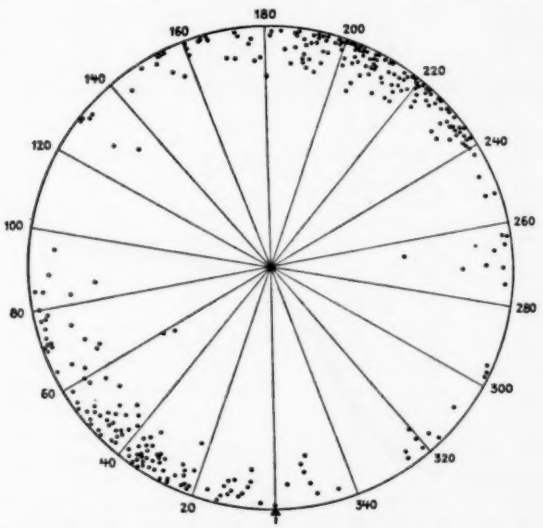

Fig. 2. Poles of biotite plotted on the Schmidt net. The diagram is divided into 20° sectors and is the sum of part-diagrams. It is an illustration and is only principally to be applied to table 1.

"ordinate" represents the 20° sectors and the "abscissa" part-diagrams A, B, C and so on. The number of poles in each part-diagram is given below the "abscissa" (table 1).

TABLE 1

Distribution of poles divided in part-diagrams and 20° sectors. From a gneiss in Blekinge, Sweden.

Sector	Number of poles					
340-360°	1	1	2	2	..	..
320-340	2	..	..	..	..	..
300-320	2	..	..	2	1	1
280-300	2	1	..	..	..	..
260-280	4	1	..	2	..	1
240-260	..	6	..	1	1	..
220-240	8	7	4	5	6	3
200-220	10	7	11	13	7	10
180-200	7	6	6	8	6	5
160-180	1	0	2	2	2	6
140-160	1	2	3	2	..	3
120-140	..	1	..	..	3	2
100-120	..	..	..	2	..	..
80-100	1	..	2	..	2	1
60-80	3	1	6	7	3	1
40-60	5	3	5	3	3	7
20-40	3	9	3	6	5	5
0-20	4	3	4	4	..	..
Part-diagram	A	B	C	D	E	F
Total	59	53	53	59	44	45 = 313.

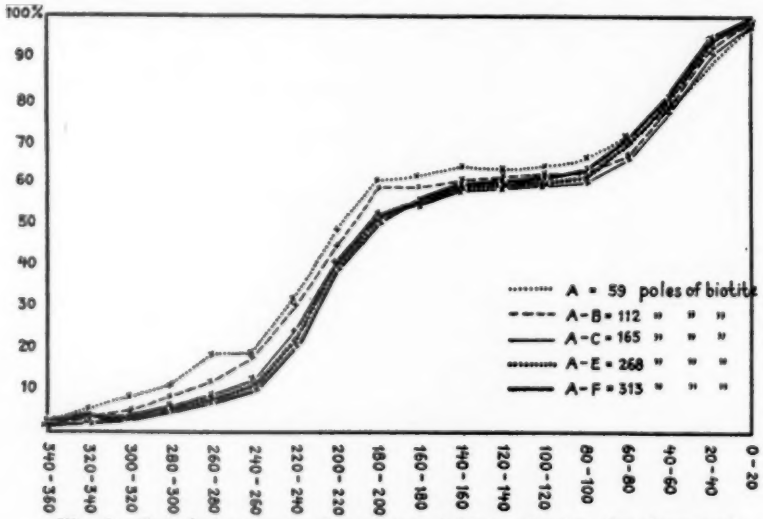

Fig. 8. Cumulative curves drawn from table 8, showing the change of the distribution of poles by increasing number.

Table 2 shows in the same manner the distribution in part-diagram A (59 poles), A+B (112 poles), A+B+C (165 poles), A+B+C+D+E (268 poles) and A+B+C+D+E +F (313 poles).

TABLE 2

Sector	Number of poles				
340-360°	1	2	4	6	6
320-340	2	2	2	2	2
300-320	2	2	2	5	6
280-300	2	3	3	3	3
260-280	4	5	5	7	8
240-260	..	6	6	8	8
220-240	8	15	19	30	33
200-220	10	17	28	48	58
180-200	7	13	19	33	38
160-180	1	1	3	7	13
140-160	1	3	6	8	11
120-140	..	1	1	4	6
100-120	..	..	..	2	2
80-100	1	1	3	5	6
60-80	3	4	10	20	21
40-60	5	13	18	29	36
20-40	8	17	25	36	41
0-20	4	7	11	15	15
Part-diagram	A	A-B	A-C	A-E	A-F
Total	59	112	165	268	313

TABLE 3

The same distribution as in table 2, but in per cent

Sector	Number of poles in per cent				
340-360°	2	2	2	2	2
320-340	3	2	1	1	1
300-320	3	2	1	2	2
280-300	3	3	2	1	1
260-280	7	4	3	3	2
240-260	..	5	4	3	2
220-240	14	13	12	11	11
200-220	17	15	17	18	19
180-200	12	12	12	12	12
160-180	2	1	2	3	4
140-160	2	3	4	3	4
120-140	..	1	1	1	2
100-120	..	..	..	1	1
80-100	2	1	2	2	2
60-80	5	4	6	7	7
40-60	8	12	11	11	12
20-40	14	15	15	13	13
0-20	7	6	7	6	5
Part-diagram	A	A-B	A-C	A-E	A-F
Total	101	101	102	100	102*
Number of poles	59	112	165	268	313

* The deviation from 100% results from the reduction of the decimal fractions to whole numbers.

In order to be able to compare the distributions with increasing number of poles, table 2 is recalculated in per cent (table 3).

From the distribution of poles in table 3, cumulative curves are drawn in figure 3. The curve A represents the distribution of biotite poles after the measurement of 59 biotite poles. A-B gives the distribution of 112 poles and so on. It is natural that the curves A (59 poles) and A-B (112 poles) are more erratic than the others. It is also easy to see that all curves from A-C (165 poles) to A-F (313 poles) are practically identical. The conclusion will be that in this case it is enough to measure 165 poles of biotite. Further measurements will not change the distribution.

The present author has found it practical to draw such curves besides making the microscopical observations.

In this case the poles of the diagram are of peripheral distribution. If the poles are spread over the whole Schmidt net it may perhaps be practical to divide the net into two parts by one or more concentric circles. This makes it possible to control any change appearing in the distribution in the direction from periphery to center.

This method of control is also available for other geological work, for instance, for structural analysis and tectonical work.

It has always been a problem how many measurements are needed to get a significant picture of all joints and other fracture planes which appear in a quarry. The graphic test can be useful for such an investigation and can be made coincident with the measurements.

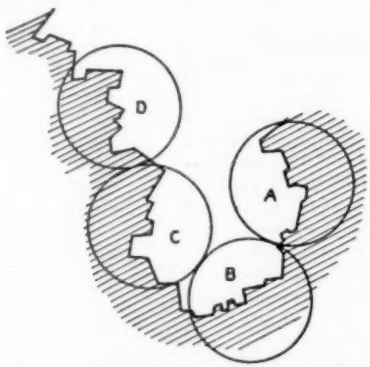

Fig. 4. A quarry in coastal gneiss in Blekinge, Sweden, divided into four parts. For each a part-diagram of the fracture planes is plotted.

It is convenient to divide the measurements of the fracture planes in a quarry into some parts, in this case 4 (fig. 4), and plot their poles on as many part-diagrams. In table 4, the fracture planes of a quarry in a coastal gneiss in Blekinge, Sweden, are described.

TABLE 4

The poles of the fracture planes in figure 4. The table is made in the same way as tables 1, 2 and 3

Sector	Number of poles								Number of poles in per cent			
340-360°	1	3	2	..	1	4	6	6	3	6	6	5
320-340	1	10	5	7	1	11	16	23	3	17	17	18
300-320	1	3	3	5	1	4	7	12	3	6	7	9
280-300	4	5	6	7	4	9	15	22	13	14	16	17
260-280	2	1	2	1	2	3	5	6	6	5	5	5
240-260	1	2	2	..	1	3	5	5	3	5	5	4
220-240	1	2	3	2	1	3	6	8	3	5	6	6
200-220	7	1	2	4	7	8	10	14	22	13	10	11
180-200	1	3	2	2	1	4	6	8	3	6	6	6
160-180	4	..	3	..	4	4	7	7	13	6	7	5
140-160	2	..	1	..	2	2	3	3	6	3	3	2
120-140	4	..	..	..	4	4	4	4	13	6	4	3
100-120	..	..	..	1	..	..	..	1	..	..	..	1
80-100	2	..	..	..	2	2	2	2	6	3	2	2
60-80	1	1	1	..	1	2	3	3	3	3	3	2
40-60	..	..	..	1	..	..	..	1	..	..	..	1
20-40	..	1	..	4	..	1	1	5	..	2	1	4
0-20	..	..	..	..	..	..	..	..	..	..	..	..
Part-diagram	A	B	C	D	A	A-B	A-C	A-D	A	A-B	A-C	A-D
Total	32	32	32	34	32	64	96	130	100	100	98	101*

* The deviation from 100% results from the reduction of the decimal fractions to whole numbers.

From the distribution of poles in per cent cumulative curves are drawn in figure 5. The four curves represent 32, 64, 96 and 130 poles of fracture planes. The curve containing 32 measurements shows a very divergent course. Probably the distribution here is determined by chance. But after 64, or better after 96 measurements, the chance seems to be eliminated. No greater change in the distribution of poles will appear with further measurements.

Figure 6 shows another quarry in the same rock. After 105 poles the curves are practically identical.

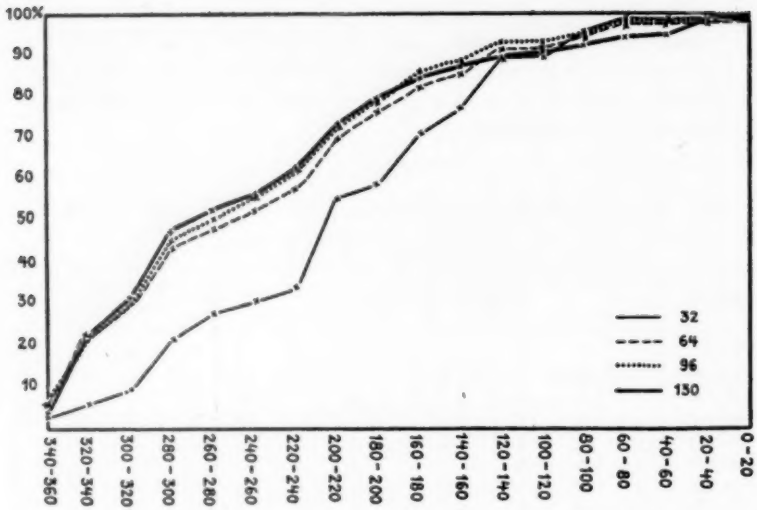

Fig. 5. Cumulative curves drawn from table 4, showing the change in the distribution of fracture planes by increasing number of measurments.

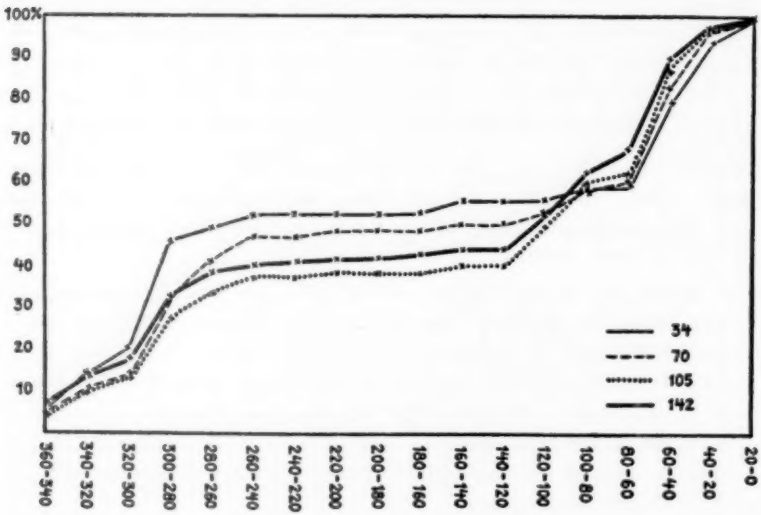

Fig. 6. Curves of the same type as in figure 5. From another quarry in the same rock.

Some critical remarks must be made. The present author has already in the introduction announced that the graphic test cannot give an exact mathematical knowledge of the amount of measurements needed for full significance at a certain security. If such criterion is needed, the papers of Chayes (1949) and Pincus (1951) may be referred to. The graphic test gives only a visual idea of the same thing. The curves are only tests of the distribution and except for that not specially practical for common geological work.

In conclusion the author may remark, in order not to be misunderstood, that in explaining his graphic method he never enters the discussion whether a single thin-section is representative of a whole rock or not. That seems to him quite another problem. The author is only dealing with the problem if the measurements in one rock-fabric are significant or not.

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ROLE OF PLANTS AND COLLOIDAL ACIDS IN THE MECHANISM OF WEATHERING

W. D. KELLER and A. F. FREDERICKSON

ABSTRACT. Plant roots accelerate the weathering of rocks by exchanging H-ions from the roots for metal (Ca, Mg, K, etc.) ions in the rocks. The metabolic energy of the growing plant implements the ion exchange.

Colloidal acid clay and colloidal organic acids of the humic type are powerful agents of weathering which also provide H-ions for a weathering process analogous to that under which plant roots operate.

The contact exchange mechanism of ion transfer via colloids plays a signicant role in weathering and other geologic processes.

The powerful aggressive action of the tiny H-ion on both silicate and carbonate rocks is emphasized.

INTRODUCTION

THE mechanism of weathering of silicates by water, as illustrated by the weathering of albite, was described earlier by Frederickson (1951). The publication of that paper stimulated a discussion of the general problem of weathering by the writers who found themselves thinking along essentially the same lines in regard to several other agents and mechanisms of weathering. It seemed logical therefore to write jointly on those aspects. The roles of plants, acid clay, and humic acids in the weathering of silicates and carbonates will be discussed along the same line as was followed in Frederickson's earlier paper.

PLANT ROOTS AS WEATHERING AGENTS

It is a matter of general geologic observation that the surface of newly exposed rock does not long remain fresh or bare in a temperate humid climate. Attack by chemical weathering begins as soon as it is wetted, but this initial alteration is strongly accelerated where algae, moss, lichens or other plants relatively low in the scale of plant evolution spread over the rock surface. Thereupon the rock surface becomes in reality an interface of intensive activity between the lithosphere and a compound atmo-hydro-biosphere. The efficacy of the latter arises from the combined actions of plant-associated H-ions, plant roots which possess exceptionally strong ion exchange properties, the driving energy of plant life process which is transmitted to the weathering system,

associated organic colloids, and residues from plant growth. Each of these factors plays a part in accelerating rock weathering.

Let us examine in greater detail the chemical effect of a plant (rootlet) which moves into contact with silicate or carbonate minerals. The surface chemistry of a plant root is similar to that of other negatively charged organic and inorganic colloids. The root (including the adhering water film) is surrounded by an ionic double layer of which the root carries a strong negative charge which is balanced by a surrounding "atmosphere" of positive ions that are characteristically hydrogen ions (Jenny and Overstreet, 1939b; Williams and Coleman, 1950; Graham and Baker, 1951). Therefore the root surface is acid in reaction. The root surface is a typical example of the well known Guoy, or Debye-Hückel double-layer system (fig. 1).

The properties of plant roots which have been determined in some detail by soil scientists and plant physiologists may be related to the effects they produce on rocks and minerals which contact the roots. Williams and Coleman (1950)

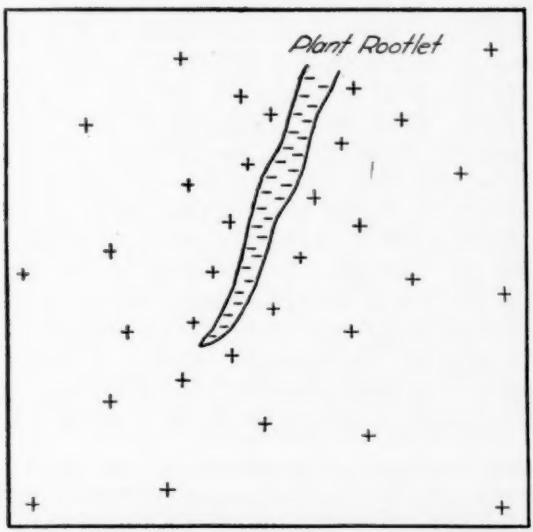

Fig. 1. Diagram of a plant rootlet which carries negative charges and is surrounded by an "atmosphere" of cations, most of which are H-ions. This is typical of the Debye-Hückel double layer.

measured[1] the pH of roots of numerous plants (barley, celery, corn, cotton, lettuce, peanut, soybean, sugar beet, tobacco, and tomato) in ambient liquids such as distilled water, carbon dioxide—saturated water, and in KCL, HCl, and HAc solutions. The pH was low (the acidity high) in all cases. In distilled water and in CO_2-saturated water (typical of geologic environments) the pH of the roots ranged from a minimum of 2.00 to a maximum of 3.85, with a mean of about 3.20. Williams and Coleman concluded that because of the relatively high acidity "presumably the population of the double layer in this case was largely H^+" (p. 245). The high concentration of H-ions at a pH of 3.0 may be emphasized by recalling that it is 10,000 times as great as at a neutral condition of pH 7. The high concentration of H-ions surrounding the roots becomes significant in the weathering attack on mineral particles. Williams and Coleman also found that instantaneous replacement of the H-ions on the root surfaces took place by cations in solutions according to the lyotropic series,

$Ba^{++} > Ca^{++} > Mg^{++} > Cs^+ > Rb^+ > NH_4^+ > K^+ > Na^+ > Li^+$.

Graham and Baker (1951) examined the cationic exchange capacities of oat, barley, rye, and wheat roots in equilibrium with their nutrient subtrates, and found as high as 14 milli-equivalent (m.e.)[2] of hydrogen per 100 gms. of dry roots of rye. Soybeans which were germinated in sand and distilled water (nutrients withheld) developed 18.0 m.e. of hydrogen per 100 gms. of dry roots after 12 days at normal greenhouse temperatures. At higher temperatures, with minimum night temperatures of 75° F., as high as 29.9 m.e. of hydrogen had developed per 100 gms. of dry roots in 12 days. These capacities may appear low in comparison to that of montmorillonite clay (80 to 100 m.e.) until it is recalled that the entire root was weighed. The exchange capacity of 100 *grams* of root *surface* (if it could be isolated) would be exceedingly high.

Roots of plants which are low in the order of development

[1] The washed roots were pressed against a glass electrode and the potential measured, using the conventional glass electrode-saltbridge technique. This pH of colloidal systems is not strictly analogous to the pH measurements of true solutions but it is the one regularly used.

[2] One milli-equivalent is 1/1000 of the equivalent weight; for example, .001 gm. hydrogen, or .020 gm. calcium.

(evolution) carry a higher concentration of H-ions than do plants of higher orders. Coleman and Williams, and Graham and Baker found more hydrogen on soybean roots (lower in order) than on tobacco and cereal roots (higher in order). Lewis and Eisenmenger (1948) studied the capacity of twenty-two varieties of seed plants from different orders of development to extract potassium from feldspar mixed with a potassium-deficient soil. They found (p. 497) "From the data it is evident that plants in the lower stages of evolution utilize considerably more potassium from both soluble and insoluble sources than do plants in the higher stages of development." From page 499, "It seems rational to inquire why the low order plants have so much greater capacity to extract the potassium ion from minerals classified as relatively insoluble. It is entirely plausible to assume that the soil in the early periods of the earth's history was not the weathered soil of today. . . . The lower non-seed plants of the early geological periods had then and now a greater capacity to use the so-called 'unavailable' ions. . . . The fact that the older seed plants are more efficient than the newer ones in obtaining their ions from what might be called 'unavailable' sources, indicates that their direct ancestors lived in an environment where frugality and slow growth were a necessity."

Geologists observe that bare rock surfaces and undecomposed rock fragments are covered and invaded by the more primitive types of plants. The chemical explanation hinges obviously on the fact that the primitive plant roots are equipped with a strong and adequate concentration of H-ions to bring about weathering of even the feldspars in fresh rocks.

Let us now consider what happens when plant roots participate in rock weathering. A tiny rootlet advances into contact with orthoclase and/or plagioclase of intermediate Na-Ca composition. The root surface is enveloped in a swarm of H-ions which are chemically aggressive because of their greater chemical potential energy arising from their high electrical charge per unit volume. Upon making contact with the jagged, irregular, broken surface of the feldspar crystal lattice, the high energy H-ions diffuse into, and are even driven by the chemical potential between H-ions and the lattice cations into the openings of the fractured lattice at the crystal boundary. Very high gradients for each cation exist on opposite sides

of the plant root interface. The H-ions are "tiny bundles of high energy, which invade aggresively the silicate lattice."

The invading hydrogen ions from the roots may coordinate with oxygen ions through the mechanism described by Frederickson (1951) and force the Na (or Ca) in the plagioclase (or the K in orthoclase) to move out. The displaced cation will be instantaneously adsorbed by the nearby root, Ca^{++}, K^{+} and Na^{+} being adsorbed in that descending order of tenacity (Williams and Coleman, 1950). Thus weathering has thereby been effected through the agency of the roots.

So far the process has been entirely one of inorganic adsorption and cationic exchange. From this stage onward, however, if the plant metabolism calls for Ca (protein synthesis), or K (carbohydrate synthesis), or Na, those elements will be assimilated by the root and plant, and removed from the chemical system. Hydrogen from the plant will be substituted at the root surface for the assimilated nutrient cation as a part of metabolism. Hence as a result of the vital activity (energy) of the plant, the original high concentration of H-ions on the root is restored, and further weathering action may proceed without reduced vigor. Energy for weathering has been indirectly supplied by the plant.

Weathering by plants does not necessarily continue at the highest possible rate because if some of the metallic cations are relatively unacceptable to plant metabolism they may build up in concentration to where they slow down the weathering process. Moreover, the other less soluble products of silicate weathering enumerated below may also act as a barrier to continued rapid weathering. These products include soluble silica gels and "insoluble silica" fragments which are derived and are released from the disintegrating silicate linkage at the surface of the original mineral. The soluble silica may be dissolved and carried far away, or it may migrate outward to the surface of the rock where by drying it may be immobilized as a hard crust, a commonly observed occurrence.

Alumina which is freed during weathering may be carried away, may remain as gibbsite (Harrison, 1933), or may relink with silica to form an amorphous compound or imperfectly crystallized clay.

Fragments of aluminum silicate crystal lattice, or "crystal wreckage," the "insoluble silica" described by Murata (1946),

resulting when some of the bonding cations are pulled out, soon will coat the underlying, unweathered mineral portion. It is expected however that rootlets will penetrate and pass through a thin layer of these weathered residues.

The first mechanism described by which the H-ions entered the silicate mineral lattice was by their coordination with oxygen ions. Another mechanism, somewhat similar to that which causes ion exchange by zeolites probably also operates. The mass action effect of a strong, concentrated cloud of H-ions on the roots will tend to exchange H^+ for Na^+, K^+, or Ca^{++} in a silicate lattice, in the same manner that a strong concentrated "recharging" solution of NaCl replaces with Na^+ the exchangeable Ca^{++} on a water-softener permutit. Commonly the movement of cations is from soil to plant, but the reverse occurs also, which is common knowledge among agronomists.

Where H-ions replace metal cations in a crystal lattice like that of feldspar, the stability of the feldspar lattice will be destroyed because the coordination of the H^+ is radically different from that of the metal cation. The silicate minerals in soils exist in various stages of decomposition and consequently the cations are held by the crystal fragments with strengths depending on the stage of decomposition of the mineral. Let us consider the availability of potassium using orthoclase (or other K-containing silicate) as the source mineral. Wood and DeTurk (1940) express the availability of potassium by the following equilibrium equation:

Primary Mineral (A K-feldspar, for example)

↓ ↓

I Fixed Potassium ⇌ II Fixed K(Acid Insol ⇌ Acid Soluble*)

Base Exchangeable

↓ ↓

⇌ III Replaceable K ⇌::: ::: ⇌ IV water soluble Potassium

* Acid-soluble potassium is potassium that can be extracted by boiling the particles in normal nitric acid for 10 minutes.

Bray and DeTurk (1938) find that outside portions of certain clay minerals may be more weathered than the inside and possess a different chemical composition as well as a different ability to exchange various cations. Minerals in this stage of decomposition would be represented by steps II and III

in the above equation. In the Putnam soil of Missouri, Marshall (1935) found that the particles included in the size range of 0.5 micron to 2 microns had optical properties as well as base exchange capacity and specific gravities intermediate between a feldspar and a clay. The x-ray diffraction patterns obtained from some colloid-size fractions of shales studied in our laboratories also can be interpreted to indicate that mineral fragments predominantly are feldspar particles in various stages of decomposition. These might represent the equilibrium between steps I and II in the above equation.

If plants or crops remove nutrient materials from clays and organic matter faster than they are released by decomposition and exchange reactions with the nutrient-reserve silt minerals in various stages of weathering, the soil becomes impoverished and fertilizers and other materials must be added to make up the deficit.

The concept that the minerals in the soils and the plants which grow from them exist in a state of dynamic equilibrium is a very important one. The plant acts as a "potential well" into which components existing in the minerals in the soil travel. By being "complexed" or utilized by the plant in metabolic processes they are effectively concentrated and removed from the system; thus the potassium in the equilibrium equation presented above moves from the left to the right. The rate at which these ions become available will then be a function of the severity of its weathering environment: the rate at which hydrogen ions from clays, organic or inorganic acids are available to attack the minerals. The cations can also be effectively removed from the system if they can be precipitated in an insoluble form or used in metabolic processes by the plant. The growth of such minerals as barite and the amphoteric oxides and hydroxides of iron and aluminum cause the equilibrium to shift from left to right, resulting in continued weathering or decomposition of the parent minerals to new mineral phases.

One of the important geological consequences of the argument presented above is that no part of the system can be changed without causing changes in the other parts. It is not enough to say that a mineral is stable; to make such a statement the environment in which the mineral exists must be specified. The clay minerals, in particular, are very sensitive to

slight changes in their chemical environment. They easily give up certain cations existing in base-exchange positions for others depending on the concentrations and activities of the ions in question (Vanselow, 1932a, 1932b) Marshall (1948) and Mukherjee and Marshall (1951).

The equation of equilibrium apparently is reversible only to a certain degree. After the outside portion of mineral has been decomposed, it can be only partially restored to its former state. Bray (1937) visualizes that some of the colloidal-sized mineral fragments in soils consist of an unweathered illite core surrounded by a weathered hull. Different portions of the mineral therefore hold potassium ions with various degrees of tenacity. If an excess of potassium ions were available, some of them would enter the lattice and lodge in sites provided by removal of these ions when the mineral was first weathered. In this manner an "old" mineral is rejuvenated instead of a new one being "created."

Of great importance to present-day concepts of petrogenesis and our understanding of the weathering process is a realization that the driving forces or energy which make these reactions take place are of a chemical nature. The various phases or parts of the equilibrium equation exist essentially under atmospheric pressures and in a temperature range determined by climatic conditions. A small increase in climactic temperature only affects the *rate* of the weathering reaction but does not result in the development of minerals of a different kind. It is recognized that the same minerals can be produced under high pressures at elevated temperatures in *isolated* systems (Roy and Osborne, 1951), but the results of such studies certainly cannot be used, at least when soils and weathering products are being considered, as "indicators" of the environment in which these minerals developed in a *geological* system or under natural conditions.

In summary, the accelerating effect on the weathering of silicate minerals by plant roots arises dominantly (1) from the high concentration of H-ions in the diffuse double ion layer surrounding roots, and (2) from the removal of the released metal cation from the weathering system.

COLLOIDAL ACID CLAY AND ORGANIC ACIDS

Colloidal acid clay and organic acids, such as humic acid, constitute additional powerful agents of weathering which act

in similar ways. Both the acid clay and the organic acids may arise as autogenous products of the weathering process which was previously described, that is, at the weathering surface between a rock and moss or other plants which spread over the rock, or they may exist as abundant exogenous constituents of the regolith in contact with unweathered rock.

The colloidal acid clay and organic acids are characterized by being composed of inner colloidal micelles which are surrounded by an outside atmosphere of H-ions. The micelle of acid clay is a hydrous silicate complex which contains aluminum and sometimes magnesium; the micelle of the humic type of organic acid is a complex organic compound. Since both of these colloidal acids exist as aqueous suspensions they may touch in most intimate contact their host rock or mineral particle.

The pH value of these colloids surrounded by H-ions is very low; it may fall below 3.0 for bentonite, and below 4.0 for humic acid (Graham, 1941a). Here then is a condition where a colloidal complex which has a large concentration and reserve of H-ion may lie in immediate contact with a rock particle which is susceptible to weathering. The attack by the H-ions proceeds as outlined previously for the acid root system.

The effectiveness of these acid colloids as weathering agents was well demonstrated by Graham who mixed suspensions of them with pulverized fresh anorthite. Within 30 days, when the first pH measurements were made, the pH of the acid colloids rose to 5 from initially 2.3 for bentonite and 3.8 for humic acid (Graham, 1941a). Calcium was unquestionably transferred from the anorthite to the colloids, as was shown by analyzing the dialyzate of the colloids.

Similarly, five grams of acid Putnam soil clay colloid (H-beidellite) extracted 3.4 per cent of the total Ca from 10 grams of silt-sized anorthite in 107 days (Graham, 1941b) Hornblende, augite, microcline, biotite, and quartz were weathered in descending intensity in the same experiment.

Where weathering of this sort taks place in a soil which supports growing plants the metal cations are removed from the soil colloids as plant nutrients by the roots. At the same time H-ions are returned by the plant in exchange for the metal cations. The hydrogen and residual film of newly released aluminum silicate combine to form a new coating of clay about

the anorthite—or other mineral surface. This newly generated clay coating is in a position to continue the weathering process on the unaltered silicate beneath it (Keller, 1947).

Continued transfer and removal of the metal cations is obviously essential to continuance of a high rate of weathering action. Such transfer may take place between colloid particles by the mechanism called *contact exchange* by Jenny and Overstreet (1939b) as well as by movement in so-called "true solution." Albrecht (1946) discussed an analogous transfer of cations across colloid particles in terms of reciprocal "hydrogen potential" and "fertility potential." The general mechanism of contact exchange may be applicable to other geologic processes than weathering, hence it merits description (the below description following Jenny and Overstreet).

Two or more colloid particles may lie closely adjacent but be repelled from actual contact (Hauser and Hirshon, 1939) because they carry similar electric charges. Negatively charged clay particles are shown in figure 2 between a negatively charged root and a mineral particle (silicate, carbonate,

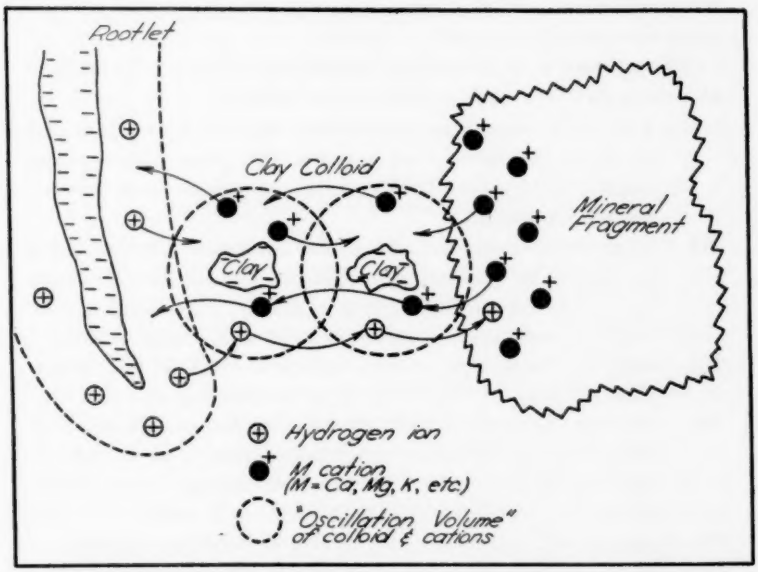

Fig. 2. Diagram illustrating the movement of cations by contact exchange between adjacent colloid particles. Modified after Jenny and Overstreet (1939b), and Albrecht (1946).

phosphate, etc.). Cations on the surface of the colloidal-sized particles oscillate around their lattice positions and hence occupy an "oscillation volume." The ions in adjacent sites can exchange if their oscillation volumes overlap, and hence can travel along this surface completely independent of the solution in which the colloidal particles are immersed. In this manner ions can migrate across these overlapping fields of force from the surface of one crystal fragment to another without ever being in "true solution." This mechanism is called "contact exchange." Plant roots, therefore, need not be in immediate contact with the surface of the silicate to implement weathering of the mineral—they need only touch the hydrated hull of the particle. Colloidal humic acid and similar colloids may be substituted for the acid clay illustrated in the chain (fig. 2) over which contact exchange occurs.

Jenny and Overstreet (1939a) also called attention to the possibility that surface migration of iron and perhaps manganese has interesting practical aspects in regard to soil color and the formation of iron concretions in soils and laterites. It can also account for the strong spotted corrosion of iron pipes buried in acid soils[3].

The movement of ions can be classified, following the outline of Jenny and Overstreet (1939a), as follows:

I.—Free diffusion of ion pairs in the intermicellar pores and channels as occurs in zeolites. To keep the crystal electrically neutral, both cations and anions—ion pairs—must be involved.

II.—The physical movement of the colloidal-sized particles on which the ions are adsorbed. Brownian bombardment or some transporting agent, fluid flow, for example, may result in movement of both particles and attached ions.

III.—Stepwise exchange of ions between surfaces and intermicellar liquids. This may be a prelude to step IV.

IV.—Surface migration and contact exchange independent of the nature of the intermicellar liquid. The movement will be random unless a concentration gradient exists. If such a gradient exists the ions will move in a net specific direction until a random distribution exists.

All of these steps may be active during the weathering pro-

[3] It might be cheaper to treat the soils than to insulate the pipe to prevent corrosion.

cess under suitable conditions. If the adsorbed water hull possesses a crystalline character as suggested by Macey (1942) and others, and described by Frederickson (1951), step IV is an example of solid state diffusion which may be effective in other geological processes as well.

CARBONIC ACID

Although the role of colloidal acids in weathering has been emphasized in this paper primarily because those acids have not received a great deal of attention in the past in geologic literature, it is not meant that the importance of carbonic acid as a weathering agent should be neglected or minimized. On the contrary, because the carbon dioxide content of atmosphere in an ordinary plant-supporting soil is commonly about ten times that of the regular atmosphere, the soil solution is significantly richer in carbonic acid than is surface water in equilibrium with the atmosphere above it. The H-ions dissociated from carbonic and bicarbonic acids are abundantly and significantly available for attacking silicate, carbonate, and other minerals by the mechanisms described earlier. Moreover, because either the carbonates or bicarbonates of the metal cations common to rocks and minerals are relatively soluble in water, they may be removed from the weathering system so that the reaction proceeds in the direction of further weathering.

WEATHERING OF CARBONATE MINERALS

Carbonate minerals constitute an important part of the rocks which undergo weathering at the earth's surface. The mechanism of the weathering of a carbonate may be illustrated by the action of an acid on calcite. Any of the acids previously mentioned (colloidal or molecular) act the same during the initial stage of weathering because the first step in the process is the attack on the crystal by the H-ion.

Calcite (and other carbonates) is especially susceptible to weathering because of its crystal structure. The structure of calcite consists of alternating Ca^{++} and Co_3^{--} ions assembled in a slightly distorted NaCl lattice (Bragg, 1937), where Na is substituted by Ca, and triangular-shaped CO_3 ions are substituted for Cl (Stilwell, 1938). The CO_3 group consists of a central carbon atom which is very closely surrounded (covalent

bonding) by three oxygens, all in one plane. A broken surface of calcite exposes potentially equal numbers of Ca^{++} and CO_3^{--} ions. The CO_3 group is particularly vulnerable to weathering attack by an H-ion because it contains large oxygen ions already highly polarized by the small, highly charged carbon ion.

During weathering of calcite, the mechanism begins with the close approach of an H-ion to the CO_3 group. The action of the H-ion may be visualized as polarizing one of the oxygens of the CO_3 group and thereby breaking away the bond of that oxygen with the C and the other two oxygens, and pulling it away. Both the carbonate ion and the calcite structure are thereby disrupted. The CO_2 remaining from the oxygen-robbed CO_3 group departs promptly as a gas—the "fizz" of calcite in acid. The CO_2 is removed from the system and thereby exposes the next Ca^{++} and CO^{--} groups to the close approach of other H-ions, an effect which promotes efficient weathering and solution of calcite by acid.

Concomitantly, the Ca^{++} ion which was released from the lattice during its breakdown associates itself with the anion of the reacting acid. The new combination may be $CaCl_2$, Ca^{++}-clay, Ca^{++}-humate, or Ca^{++}-root-system. The latter becomes H^+-root-system after the Ca is assimilated by the plant or is precipitated in the form of an insoluble mineral.

Breakdown of the CO_3 group by H-ion occurs effectively because the bond between O and H is apparently stronger than the bond between O and C. A relationship which illustrates the preferential combination of oxygen with hydrogen is the incomplete combustion of a hydrocarbon. Where oxygen is deficient during the combustion, water is formed while elemental carbon, in the form of a graphite soot, is released from the hydrocarbon. The heat of (combustion) combination of one mole of O with H is 1.45 times greater than that of one mole of O with C.

The complete energy changes which occur in the solution of calcite in acid are more involved than in the simple combustion cited, and have not been worked out in detail. Nevertheless, the initial reactants and the final products of the reaction are clearly evident, and the direction of the reaction is unquestioned.

SUMMARY

Rock weathering begins with the attack of H-ions on silicate or carbonate structures. The H-ion is pre-eminently effective because its tiny size permits physical entry into "solid" structures, and because of its unique and high energy "hydrogen-bonding" chemical properties arising from its large charge for such a small size.

Hydrogen ions may be furnished by strong mineral acids (HCl, HNO_3, etc.) in solution, but the acids most abundantly available in geologic process and which perform the bulk of weathering are water, carbonic acid, plant root systems, acid clay, acid humus, and various complex organic substances. In the growth process of plants, the H-ions appearing on the surface of the roots are exchanged for nutrient metal cations coming from rock and mineral particles. The energy of the growing plant is therefore diverted in part toward promoting rock weathering.

Cationic transfer may be accomplished along a network of colloidal particles by the contact-exchange mechanism. This process supplements transfer in molecular solution.

Weathering or disintegration of a silicate lattice may occur by the polarizing effect of H-ions on the oxygen, as described by Frederickson, and by mass action, ion-exchange effect analogous to the permutit exchange.

Weathering of the carbonate structure is achieved by polarizing and removing an oxygen from the CO_3 group, and concomitant removal of the metal cation.

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A CONTRIBUTION TO THE PLEISTOCENE FAUNA OF NEW YORK STATE

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ABSTRACT. An addition to the Pleistocene mammalian fauna of New York State is reported in the form of a fossil antler of the barren ground type of caribou, *Rangifer arcticus* (Richardson). The specimen was discovered two miles north of Schenectady, New York, and thirty feet below the present surface in crossbedded gravel associated with the marginal lacustrine deposits of glacial Lake Albany.

INTRODUCTION

FOSSILIZATION of ancient land animals is pure chance; their subsequent discovery is likewise commonly fortuitous. The case under consideration is a typical example.

While operating a sand digger in a sand and gravel pit 0.3 mile north of the intersection of the Swaggertown and Worden roads and 0.5 mile northwest of the Schenectady County airport (fig. 1), Mr. Charles Aubrey uncovered fragments of an antler of the family Cervidae. Verification of the remains as those of a caribou antler was made by Dr. Ralph S. Palmer, State Zoologist of New York. Through the efforts of Mr. Ostrom, the specimen currently reposes in the Department of Geology at Union College.

The preponderance of proboscidean remains over those of the Cervidae in Pleistocene deposits of eastern North America does not necessarily imply that the mastodons and mammoths were numerically superior. It seems probable that in the past, as today, the deer family far outnumbered their proboscidean cousins, but their relatively smaller skeletal parts were more susceptible to destruction than those of the more massive mastodons and mammoths. It is for this reason that the finding of fossil deer remains is a much rarer occurrence.

Within New York State, the earliest record of the finding of remains that are questionably referred to those of caribou is that of Ebenezer Emmons (1845, p. 201) in which it is reported that a jaw of an extinct species of deer was found in Greene County in a marl pit and later a "horn" from a similar pit in Scotchtown, Orange County. Emmons states, "This deer was about the size of the reindeer of the north, and like that animal, was provided with a flattened (though more

slender) horn; but it differs specifically from the reindeer, in the possession of two brow antlers instead of one, on a single shaft, and quite near the base." It is now known that the possession of two brow antlers is not uncommon. Hartnagel and Bishop (1922, p. 90) assert that, "The antlers found were probably those of the barren ground species, *Rangifer arcticus* (Richardson)." The brevity of the original description, however, would not seem to favor a specific designation for this specimen. In his summarization of Pleistocene mam-

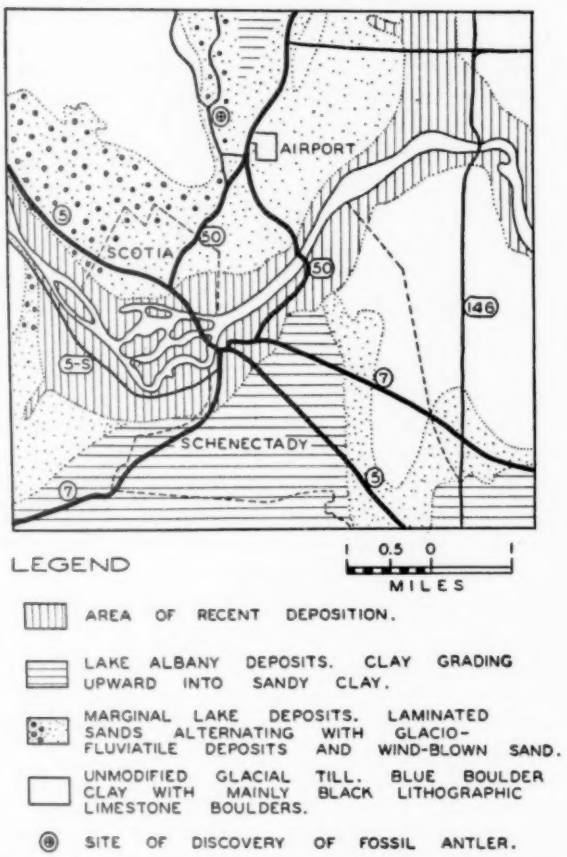

Fig. 1. Sketch map showing the glacial geology of the vicinity of the fossil caribou antler locality. (Modified from Stoller, 1911.)

mals, O. P. Hay (1923) omits mention of this discovery, either considering the find to be other than that of a caribou or else inadvertently overlooking it.

In 1853, an antler and parietal bone of a caribou were discovered in a peat bog, 6 feet below the surface, at Fairytown, New York. However, the report of this find was not published until some 70 years later (Norton, 1924, pp. 132-133). The antler now rests in the Society of Natural History at Portland, Maine. The main shaft has a length of 23½ inches (59.7 cm.), a diameter of 1¼ inches (3.2 cm.) just above the burr, and one branch 8 inches (20.3 cm.) in length, 4½ inches (11.4. cm.) from the burr; both have broken tips. Due to the lack of completeness of the specimen it is impossible to classify it further than to say that it is definitely a caribou antler.

Joseph Leidy (1860, p. 194) related an account by Dr. G. J. Fisher of the finding of an antler of a reindeer in the vicinity of Sing Sing, N. Y. The specimen was found 6 feet below the surface in a peat bog almost an acre in extent that appeared to be the site of an ancient lake. It is further stated, "Dr. Leidy observed that there is a similar specimen of an antler of a reindeer in the museum of the academy which had been found near Vincentown, New Jersey at a depth of four feet. . . ." It is regrettable that the dimensions of the antler were not recorded for the whereabouts of the specimen is unknown. If we are to rely on Leidy's observation of the similarity to the accepted caribou find in the museum of the Philadelphia Academy of Natural Sciences, then Fisher's account is a valid caribou discovery.

Almost a century has elapsed since the last remains of fossil caribou have been found within the Empire State. This, together with the lack of adequate description and location of previous discoveries, prompts the writers to present the information embodied in this article.

GEOLOGIC SETTING

The stratigraphy at the discovery site (fig. 1) is as follows:

Post-Pleistocene:

9-10 feet	Yellowish-brown sandy loam intermingled with "blow" sand consisting of fine subangular frosted quartz grains denoting an aeolian origin.
0-3 feet	Crossbedded pebble gravel channeling the underlying lacustrine deposits.

Pleistocene:

6 feet	Laminated coarse grain sand; angular to subangular quartz grains constitute about 90 percent of the deposit. The remainder consists of kaolinized feldspar, hornblende, chlorite, mica, shale fragments, and some garnet. The grain size averages 1 mm. in diameter. Lake Albany sediments.
16 feet exposed	Coarse crossbedded river-laid gravel intermingled with coarse sand and here and there interbedded with fine wind-blown sand. Interpreted as foreset beds formed in Lake Albany. Fossil antler found 2 feet above floor of pit.

Stoller (1911) mapped these sediments as near-shore deposits in Lake Albany. At its maximum, this transient Pleistocene lake occupied that part of eastern New York extending from Fort Ann on the north to Kingston on the south and extending for some 25 miles eastward from a point 4 miles west of Schenectady (Woodworth, 1905, pp. 176-178). The gravel in which the specimen was found is considered to be deltaic sedimentation of the Iromohawk River, a name applied by Fairchild (1912, p. 32) to the period of glacial flow of the outpourings of glacial Lake Iroquois and the other Great Lakes through the Mohawk Valley. Angular and subangular cobbles of Schenectady sandstone, a Middle Ordovician formation which does not extend farther than 10 miles west of Schenectady, imply a short distance of transportation and close proximity to the source. Marginal type sedimentation is clearly shown all along the southern and eastern rim of the "Glenville Hills," a relatively high area to the northwest of Schenectady not inundated by the Iromohawk waters.

DESCRIPTION

Grant (1902, p. 176) divides all members of the genus *Rangifer* into two groups, the barren ground caribou and the woodland caribou. The distinction between the two divisions is based on antler architecture. The antlers of the barren ground group are round, slender, and long in the main beam in proportion to the small size of the animal. The beam and the tines are but slightly palmated and have less than thirty points. In contrast, the woodland caribou possesses antlers which are flatter, thicker, short in the main beam, liberally palmated on both the beam and tines, and have more than thirty points. The bez tine, the tine immediately above the brow antler, is elaborately developed in the woodland caribou and Grant (p. 182) considers this the most distinguishing feature sep-

arating the two types. Conforming to this accepted division, the specimen under discussion represents an antler of the barren ground type of caribou, and comparison with the descriptions and illustrations of the five modern species discloses that it is conspecific with *Rangifer arcticus* (Richardson) (fig. 2). It is so classified because of the virtual nonpalmate character, few points, long main beam, and general "arm chair" appearance. The sole divergency in likeness to the modern *R. arcticus* is that the described fossil shows the main shaft to terminate in a gradually tapering single point whereas the living species all show a multiple pointed palmate tip. This is interpreted as a minor variation of antler architecture for it has been shown that there is extreme diversity of antler configuration in all of the Cervidae. Nonetheless, there are certain basic characteristics of antler structure which may be utilized for identification with reasonable assuredness. It is for this reason that the antlers of the barren ground type of caribou are said to have an "arm chair" appearance while the woodland caribou presents a "treetop" appearance (Hornaday, 1904, p. 133).

The fossil is a fairly complete left antler with a beam 51

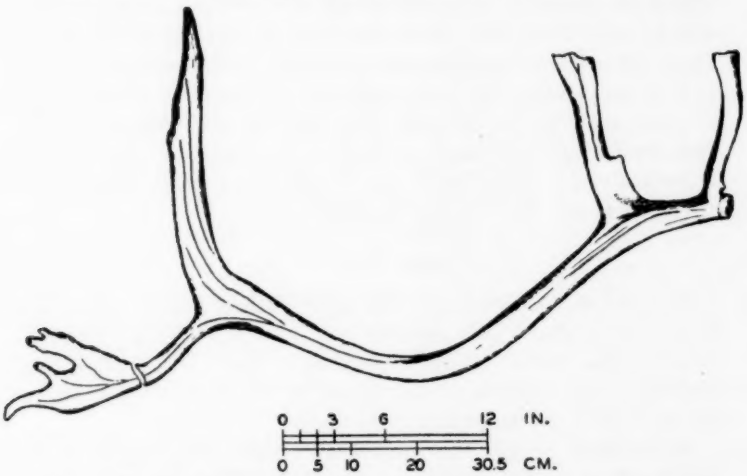

Fig. 2. Sketch of antler of *Rangifer arcticus* (Richardson). Note particularly the singular pointed main shaft and the roughly parallel grooves indicating the positions of the veins leading to the blood vessels when the antler was in the velvet stage.

inches (129.5 cm.) in length and 1½ inches (3.8 cm.) in diameter at the burr (fig. 2). Slight palmation is first apparent 27 inches (68.6 cm.) from the burr but continues for only some 10 inches (25.4 cm.) toward the gradually tapering, rounded single point of the main shaft. Bifurcation of the main shaft occurs 32 inches (81.3 cm.) from the burr where a broken branch increases the total spread an indefinite amount.

Both the brow and bez tines are partly broken off. The former is 7¾ inches (19.7 cm.) in length and 2¼ inches (5.7 cm.) in width at the broadest point. The latter has 10 inches (25.4 cm.) showing and is 2 inches (5.1 cm.) wide at the broadest point. Both are but slightly palmate in character. Noteworthy is the fact that the brow tine is only ⅜ inch (1 cm.) from the burr; the bez tine is 5 inches (12.7 cm.) from the point of attachment to the skull.

There are nine points preserved but doubtless this does not represent the original number. Three of the points could not be fitted into the mounted specimen but presumably were part of the brow and bez tines.

In the region of bifurcation of the main shaft, three prominent grooves exist roughly parallel to the length of the beam. These impressions evidently mark the position of the veins which led to the blood vessels when the antler was in the velvet stage. Hardened brown areas adhering to the surface of the antler are interpreted as remnants of the original velvet.

It is difficult to estimate the size of the animal in life for barren ground caribou have large antlers relative to their body size. This produces the effect of magnifying both the height and bulk of the wearer.

SIGNIFICANCE

The current discovery is the third authenticated one of its kind in New York State and the first in eastern North America in which the antler was preserved in gravel (Hay, 1923, pp. 224-245). In addition, illustrations of fossil caribou remains prior to this publication are lacking.

Some idea of the environmental conditions prevailing in this portion of the country during the latter stages of the waning Wisconsin ice sheet may be obtained, for presumably the modern *Rangifer arcticus* frequents much the same type of habitat as his Pleistocene predecessors. This would suggest that tundra conditions existed adjacent to Lake Albany

in which the region appeared as a virtually treeless landscape with only low-growing vegetation. Evidence of wind-blown sands lends impetus to the supposedly treeless condition, for dune sand is whipped about only where obstacles such as trees are scarce or absent. This species of caribou evidently migrated northward as the ice waned, for today *R. arcticus* is not found south of the fifty-fourth parallel. The most southerly penetration recorded is in the vicinity of the eastern shore of the juncture of Hudson and James bays (Grant, 1902, map).

It is thought that the fossil represents a shed antler for no skeletal bones were found associated with it. If the antlers were attached at death, it would be thought that some of the more resistant portions of the skeleton such as the teeth, skull bones, or leg bones would have been preserved inasmuch as the less resistant antler fragments were preserved so splendidly. Undoubtedly quick burial due to rapid deltaic sedimentation favored the preservation.

The location of discovery poses somewhat of a problem. Assuming that the Adirondacks were completely covered by continental ice and that as the ice melted the Adirondack island slowly became larger, it is rather perplexing to understand just how the antler happened to be found on the northwest shore of Lake Albany, when presumably that was the Adirondack island side of the lake (Fairchild, 1912, plate 17). The assumed volume and turbulence of a river such as the Iromohawk seems to preclude the possibility that the caribou could have swum to the northern bank. It is conceivable that at this stage in the recession of continental ice, the Adirondacks may have had an eastward land connection and that the glacial waters of the Champlain and Hudson valleys were separated by land in the Fort Ann-Whitehall area, although Woodworth (1905, pp. 177, 178) implies the two valleys to have a water connection. The writers favor the theory that the antler was not shed at the spot where it was ultimately found, but that it was carried to its discovery site by the waters of the Iromohawk. The abnormally high velocity and volume would prevent the antler from sinking to the bottom and, on entering the open water of Lake Albany, the velocity would be checked causing both the antler and the detritus carried to be immediately deposited.

Due to the recent findings of Flint and Deevey (1951), our

concept of the time that has elapsed since the last ice sheet (Mankato) began to wane has been considerably shortened. The whole process of deglaciation has seemingly progressed more rapidly than has heretofore been supposed. Recent radiocarbon dating determinations place the earlier part of the draining of Lake Iroquois as 4,930±260 years ago and the early Nipissing stage of the Great Lakes as occurring 3,656±640 years ago (Flint and Deevey, 1951, pp. 264, 265). On the basis of this recent information and judging by the antler's position with respect to the Iromohawk deltaic deposits, the fossil is estimated to be approximately 4,500 years old.

Sincere thanks are extended to Dr. William R. Evitt of the University of Rochester for reading the completed manuscript.

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REVIEWS

Basic Theories of Physics: Heat and Quanta; by P. G. BERGMANN. Pp. xii, 370. New York, 1951 (Prentice-Hall, Inc., $6.70).—Sensitive physicists are becoming increasingly aware of two coordinated evils that beset the teaching of their subject: courses crammed full of subject matter and blindness with respect to the niceties of scientific method. These terms characterize the pedagogical situation in physics rather brutally; they express what more tactful persons would speak of as a wholesome desire for completeness and a clear focus upon scientific fact. Gradually, the negative aspects of these euphemisms are beginning to worry the writers of textbooks, and encouraging results are coming into view.

Bergmann's book, though apparently not conceived by its author as an antidote to the mentioned evils, is novel and noteworthy primarily because it does show how to avoid them. Its subject matter does not cover the field of heat or of quanta as completely as other books; rather, it represents a selection of important topics held together by a slightly unorthodox web of analysis and, more notably, by the author's consuming interest in fundamental method.

Departures from custom are particularly apparent in the treatment of heat, where the point of view of modern statistics, which is based on measure theory, is quite frankly adopted. To be sure, this makes the derivation of relatively simple formulas, like Maxwell's distribution law and the law of equipartition, quite long and cumbersome. Some teachers will object to Bergmann's approach on these grounds. But the meticulous student will perceive the enormous gain that accrues from the acquisition, once and for all, of a set of powerful analytic tools that can be used on difficult problems when they are sharpened on simple ones. My own taste would have been more thoroughly satisfied had I seen, here and there, a brief recapitulation of traditional proofs, even by way of criticism—but it is hardly fair to chide a scientific author for failing to align himself with the past.

There are places in the book where the heavy rigor of the mathematical treatment lightens, where the text seems to say: let us pause and take stock of the meaning of things. Such siestas are much too rare in our normal teaching day, and it is a pleasure to see that Bergmann's book suggests them. If I were to criticize this novel and striking volume, my stricture would be the wish that more had been done, in a truly philosophic vein, with these potent pauses in a uniformly excellent book. HENRY MARGENAU

Principles of Ionic Organic Reactions; by (the late) ELLIOTT R. ALEXANDER. Pp. viii, 318. New York, 1950 (John Wiley & Sons, Inc., $5.50.—A number of reactions in the field of organic chemis-

try are presented from the point of view of reaction mechanism, with the discussion based on the modern picture of ionic intermediates. The ideas of resonance, hyperconjugation and steric hindrance are applied to reactions in the field of organic chemistry with little attempt made to cover the quantitative aspects or physical basis of these effects. The result is a concise, qualitative correlation of considerable useful information which is ideally suited for advanced undergraduates and first-year graduate students.

The book is very well documented with references to the original literature, and is excellently organized. Students will find here the best available practical guide to the use of some of the modern concepts of organic chemistry. HARRY H. WASSERMAN

The Structure and Mechanical Properties of Metals; by BRUCE CHALMERS. Pp. ix, 132; 89 figs. New York, 1951 (John Wiley & Sons, Inc., $3.50).—Although the audience for whom this little volume is intended is not precisely defined, the author clearly excludes the specialist or "serious student of the physics of metals." In fact, only a knowledge of elementary physics and chemistry is considered to be prerequisite to the reading of this monograph and even this meager background is not greatly utilized. The author, in 123 smaller-than-average pages, hopes to provide the reader with a fair understanding of the entire field of physical metallurgy starting from the structure of the atom and atomic forces. This apparently impossible program is actually carried through rather well, although obviously with extreme brevity. From a discussion of atomic forces, the reader is lead into a description of the structure of pure metals, including a discussion of solidification and grain boundaries, thence to alloys and a description of the principal equilibrium diagrams and reactions in binary alloy systems. The most elementary concepts of plastic deformation are then presented, followed by a discussion of the various changes produced by heat treatment. Finally, the last chapter, which constitutes one third of the book, attempts to classify and discuss the various mechanical properties studied in engineering applications of metals.

In spite of the brevity of the presentation, it is both coherent and stimulating. Even the reader who has been widely exposed to the study of metal physics will find many sections that are thought provoking.

The last chapter on mechanical properties will perhaps appear disillusioning to the intended reader who has been given the impression that everything presented earlier will serve as background for an understanding of mechanical properties. Instead he will find that the treatment of this subject not only ignores most of what he has already learned, but it brings him into a new field more special-

ized and more complex than the material of the earlier chapters. The first eighty pages of this volume could well stand alone as a lucid presentation of the basic aspects of the structure of metals for the non-specialist. A. S. NOWICK

Principles of Petroleum Geology; by WILLIAM L. RUSSELL. Pp. xi, 508; 1 plate, 132 figs., 8 tables. New York, 1951 (McGraw-Hill Book Co., Inc., $7.00).—Russell's *Principles of Petroleum Geology* is a new entry into the field of recently published texts for use in courses dealing with the application of geology to the search for petroleum. The author has set for himself the job of discussing in detail the processes, techniques, and basic principles employed by those whose task it is to discover petroleum. In the opinion of the reviewer, the author accomplishes his purpose with distinction.

Before invading the technical aspects of the complex study of petroleum, the reader is introduced to a few comments regarding the nature of an oil company geologist's work, what academic training he should receive, the organization of a typical oil company, and the types of drilling rigs used by the industry.

The chapters dealing with the chemistry of natural hydrocarbons and physical properties of petroleum are rigorous, without attempting to be exhaustive. A chapter on oil-field waters is included before geologic matters are broached.

A short summary of the methods of representing geologic data prefaces the consideration of the geologic aspects of petroleum. In this chapter the author proposes the term "paleoareal" for geologic maps showing the distribution of various formations in past geologic time. How this term differs from the commonly used term "paleogeologic" map is not clear to the reviewer.

A discussion of the structures in which petroleum occurs and the types and properties of reservoir rocks leads logically into the detailed structural-stratigraphic classification of oil traps presented in chapter 9. Numerous examples and figures are incorporated into the chapter on classification.

Chapter 10, subsurface pressures, recounts the present state of knowledge on a complex subject about which little is definitely known. The reviewer would suggest that this chapter might be included with the material on the physical and chemical properties of petroleum because of the possible effects of changes in pressure on the physical and chemical properties of petroleum.

The origin of petroleum is considered from the inorganic and organic point of view. The author rejects the abyssal origin and generation from natural gas theories and leans toward the idea that bacterial action on the organic content of sediments may be a large factor in transforming solid hydrocarbons into petroleum.

He proceeds with a discussion of the nature of the organic content of sediments and how this organic material might be affected by such physical agencies as temperature, pressure, and radioactivity. Turning to the field evidence as the ultimate court of appeal, the author concludes that the only safe generalizations about source rocks for petroleum are marine origin and fineness of grain size. But how source rocks are distinguished from the finger-grained rocks that serve as seals for the oil remains an enigma.

Chapter 12, the migration and accumulation of oil and gas, is especially well done in the opinion of the reviewer. The four main theories of accumulation—fracture theory, gravitational theory, hydraulic theory, and capillary theory—are discussed at length. The historical review of the development of these ideas and their application is the story of the petroleum industry, and the author logically includes his historical review with the discussion of the theories rather than as a separate chapter on the growth of the petroleum industry as a whole.

The author has collected and listed a series of geologic limits that any theory of oil and gas accumulation must meet and launches into a discussion of the possible mechanisms of migration in light of the various theories, his tests, the field facts, and certain experimental evidence. The author has done an excellent job in gathering the available information on this matter and presenting it judiciously.

Regional alteration and the carbon-ratio theory are explained in chapter 13.

Although he has presented his structural-stratigraphic classification of oil traps previously (chapter 9) the author next adds several chapters dealing with the relationship of oil and gas to unconformities, special depositional features (reefs, wedges, etc.), and salt domes. He also discusses briefly the various surface indications of oil and gas.

Most of the remainder of the book (chapters 18 through 24) is concerned with the subsurface, geophysical, and geochemical methods used by the petroleum industry. The several methods for logging wells are explained, as are the surface geophysical methods of obtaining subsurface data. Seismic methods are treated separately in chapter 24.

The closing chapters of the book summarize the development of oil and gas fields after discovery, the search for oil on the continental shelves, and the future outlook of the petroleum industry. A summary of the methods of finding stratigraphic traps, perhaps the central concern of oil companies today, is the subject of chapter 26.

The author is to be complimented for the way in which he has

written this book. Examples from various types of oil fields are woven into the text to supplement the discussion of types of oil traps. Systematic descriptions of the geology of oil fields of the United States or the world, which take up large parts of many textbooks on this subject, fortunately are not included and the author has succeeded in remaining close to his chosen title. Although one might question the exact order of the chapters, the organization of each chapter is coherent and the writing done with care. Illustrations are clearly drawn and careful editing has removed text errors. It is perhaps unfortunate that no bibliography is given, either at the end of each chapter or at the end of the book; the references are listed in full as footnotes. However, this feature does not detract from the high quality of the book.

JOHN E. SANDERS

Southeast Asia; by E. H. G. Dobby. Pp. 415; 118 figs. London, 1950, and New York, 1951 (University of London Press, and John Wiley & Sons, Inc., $5.00).—Professor Dobby deserves our thanks for having undertaken the task of writing the first general geographic survey in English on Southeast Asia and thereby filling a very noticeable gap in geographic literature—a gap felt by teachers and students alike, especially if they do not have access to German, French, and Dutch treatises on Southeast Asia. Years of residence in Singapore and extensive fieldwork qualify Professor Dobby for the writing of this book which, in the words of the author, "is to present a picture of environmental conditions and human adaptations in Southeast Asia which shall provide the student with a basic text and at the same time stimulate the sociologist, the administrator, the politician and the businessman to see the relation of their work to the general field."

The author has achieved the first objective, of providing a basic text. His lay audience may find the opening chapter on geology a stumbling block. In future editions, a general introductory chapter defining the term Southeast Asia and describing the character and the significance of the region is recommended.

Professor Dobby presents his materials in three parts. The first part, entitled "The Natural Landscape of Southeast Asia" (pp. 1-84), deals with the physical environment; the second part, "The Countries of Southeast Asia" (pp. 85-344), treats the natural and cultural elements in the geography of the various countries, i. e., Burma, Thailand, Indochina, Malaya, Indonesia, and the Philippines; while the third part, "The Human Geography of Southeast Asia" (pp. 345-398), consists of four chapters dealing with "Agriculture," "Fisheries," "Industry and Trade," and "Peoples, Politics and Prospects" of Southeast Asia as a whole. It is probable that

the organization would have been stronger and that less repetition would have been necessary if most of the subject matter of the third part had followed Part I, so that the reader would earlier become familiar with peoples and cultures and all those basic activities and problems that are common to all countries of Southeast Asia.

In Part II Malaya and Burma are treated in three chapters each, dealing with "Natural Landscape," "Cultural Landscape," and "Social Landscape," respectively. Sumatra, Borneo, the Eastern Islands of Indonesia, and the Philippines have each only one chapter covering physical and cultural geography; Java, Thailand, and Indochina are treated each in two chapters dealing with "Natural Landscape" and "Cultural and Social Landscape." The best chapters are those dealing with Malaya and Burma. The other chapters are somewhat uneven in quality.

It is unfortunate that the book has more than its share of typographical errors and that a number of erroneous statements have crept into this edition. A book of such scope as this really should be submitted prior to publication to specialists on the various topics and countries covered. The occurrence of factual errors is a serious handicap to the student or layman who relies upon this book for reference purposes, unless he has some guidance. For instance, in the chapter on the Philippines the author gives reasons "for the subdued development of Filipino commercial crops" (pp. 332-333) but does not mention the most important one, the Public Land Law, which prevented corporations from acquiring more than 1,024 hectares of public land, so that American companies in search for rubber land turned to Malaya and Sumatra rather than Mindanao. An American student will be surprised when he reads (p. 333) that "the virtual autarchy of North America operated against the production of Filipino sugar, which had to compete with Cuban and Louisiana cane . . . ," since he knows that the Philippines has benefited from American tariff legislation, that it has enjoyed an assured sugar quota for many years, that it had preferential treatment compared with Cuba, and that it will enjoy special privileges until 1974. A familiarity with Bauer's book "Rubber," a must for a specialist on Southeast Asia, would have prevented the contention that (p. 211) "the actual acreage under rubber (in Sumatra), the chief smallholder cash crop, cannot be listed accurately . . ." The Dutch conducted a fairly reliable census of the rubber smallholdings of Indonesia shortly before the war in their attempt to curtail the rubber production of Indonesian smallholders.

The book is well illustrated by more than 100 maps and diagrams. The reviewer would like to plead with the publisher for even more maps in a future edition, particularly for location maps for each country.

KARL J. PELZER

Introductory Botany; by ALEXANDER NELSON. Pp. viii, 479; 121 figs. Waltham, Mass., 1949 (The Chronica Botanica Co., $3.75).—In the plant sciences, as in practically all other biological fields, emphasis in elementary teaching has recently swung towards physiological functions, and the neophyte frequently finds himself woefully unfamiliar with the morphological and anatomical peculiarities of the organisms he studies. For the teacher who still believes that a knowledge of function should be anchored upon a basis of structure, the present text will provide a condensed and straightforward account of plant taxonomy, morphology, and anatomy. Perhaps the major criticism which must be leveled at this book is the very superficial and out of date treatment accorded even the basic physiologic functions of photosynthesis and respiration.

The style is clear and unequivocal and the diagrammatic illustrations are well conceived. The text will no doubt prove useful in those secondary school and elementary college courses which are based upon the descriptive phases of plant science.

VICTOR M. CUTTER, JR.

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